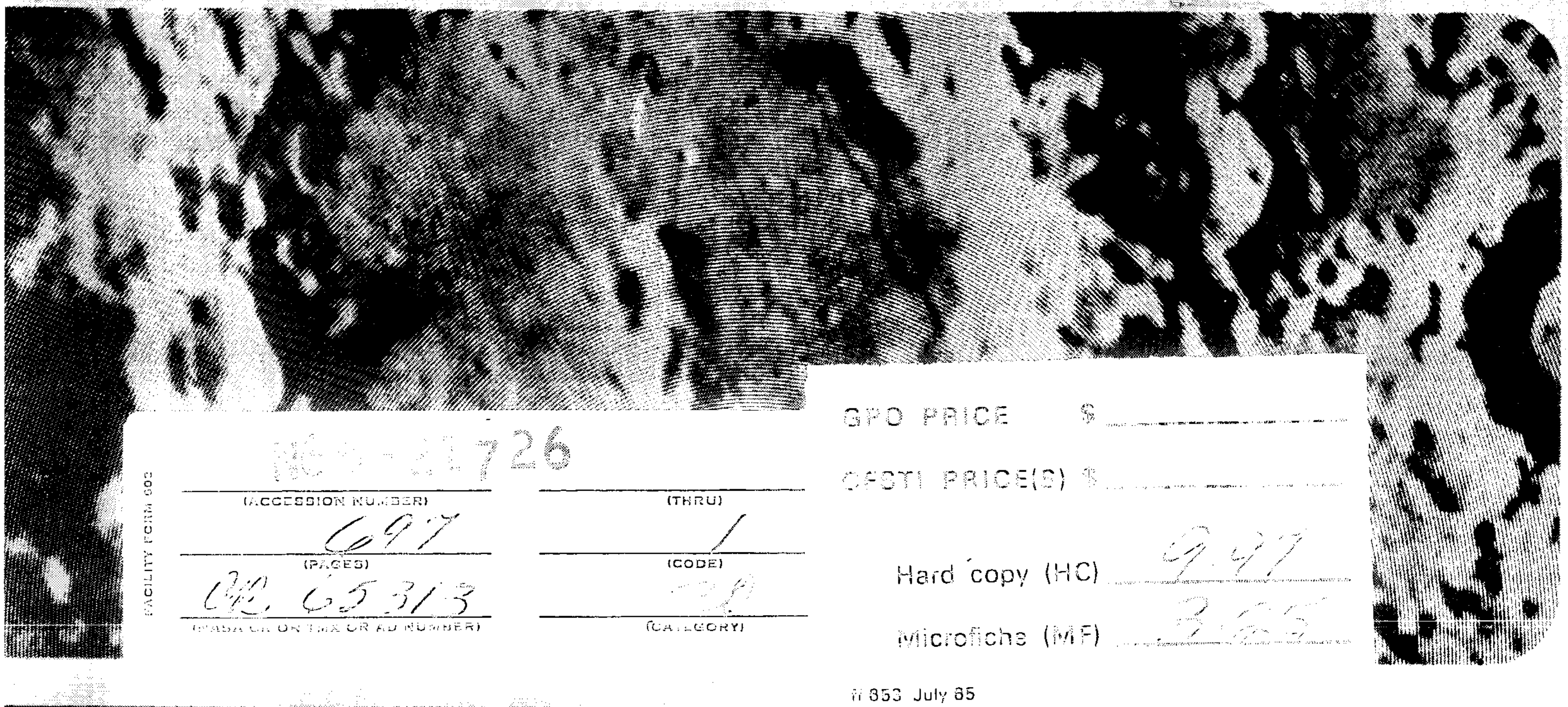

SURVEY OF LUNAR SURFACE MEASUREMENTS EXPERIMENTS AND GEOLOGIC STUDIES

CONTRACT NO. NAS 9-2115
FINAL REPORT

TEXAS INSTRUMENTS
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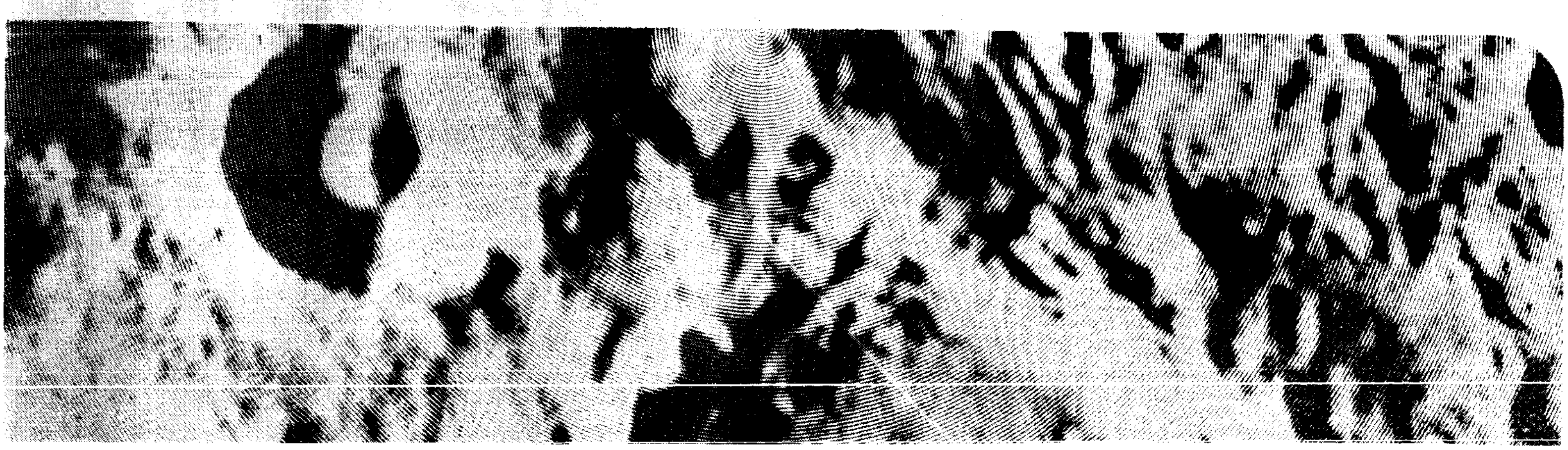

SURVEY OF
LUNAR SURFACE MEASUREMENTS, EXPERIMENTS
AND
GEOLOGIC STUDIES

FINAL REPORT

CONTRACT NO. NAS 9-2115

AUGUST 30, 1964

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON 1, TEXAS

TEXAS INSTRUMENTS
INCORPORATED
SCIENCE SERVICES DIVISION
6000 LEMMON AVENUE
DALLAS, TEXAS

FOREWORD

Contract No. NAS 9-2115 was awarded to Texas Instruments Incorporated on September 30, 1963. The award was based on evaluation of a proposal submitted by Texas Instruments in response to RFP No. MSC-63-713p issued by the NASA Manned Spacecraft Center on June 24, 1963. The program was undertaken to determine optimum measurements, experiments and geologic studies to be made on the lunar surface during early APOLLO missions. Primary consideration has been given the following phenomena and properties: gravitational, magnetic and electrical fields; seismicity; distance and location (planimetric and elevational position); composition and age of lunar features and material; geochemical and geonuclear properties; rheologic and soil mechanics properties; surface geometry (macro- and micro-relief); temperature and thermal conductivity; stratification and density; and radiation, particle and micrometeoroid flux. Arthur D. Little, Inc. (ADL) was employed as a subcontractor to assist in the study of thermal, micrometeoroid, chemical reactivity, and radiation properties and phenomena.

The subject contract provided for a multidiscipline effort extending over a ten-month period. Dr. Jack R. Van Lopik and Dr. Richard A. Geyer were assigned technical responsibility for the program. Administrative and managerial functions were performed by Dr. Howard E. Sorrows and Mr. Ritchie Coryell.

The program was conducted on a task force basis and various individuals were assigned responsibility for specific areas. The chapter headings of this report provide a convenient outline for indicating contributions of program personnel.

PART I

I.	INTRODUCTION	Dr. J. R. Van Lopik, Geologist Dr. R. A. Geyer, Geophysicist
II.	RECOMMENDATIONS	Dr. J. R. Van Lopik, Geologist Dr. R. A. Geyer, Geophysicist
	Contributing Personnel:	Mr. F. E. Romberg, Geophysicist Dr. R. O. Stone, Geologist Dr. A. E. Sobey, Physicist
III.	MISSION PLANNING TECHNIQUES	Mr. F. E. Romberg, Geophysicist

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	Composition	Dr. D. F. Saunders, Geochemist Mr. H. J. Belknap, Analytical Chemist
	Radiologic	Dr. P. E. Glaser, Physicist (ADL) Dr. A. E. Wechsler, Chemical Engineer (ADL) Dr. P. S. Thayer, Microbiologist (ADL)
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	Seismic	Mr. F. E. Romberg
	Magnetic and Electrical	Dr. R. A. Geyer
III.	SOIL MECHANICS	Mr. R. E. Becker, Soils Engineer
IV.	SUPPORT TECHNOLOGIES	Mr. N. C. Harding, Geologist-Geophysicist
	Sampling Techniques	Mr. J. E. Arceneau, Geologist-Geophysicist
	Surveying, Mapping and Photography	Mr. N. C. Harding Mr. P. D. Call, Physicist
V.	ENGINEERING PROBLEMS AND CONSTRAINTS	Dr. A. E. Sobey, Physicist
	Contributing Personnel:	Dr. R. C. Johnston, Jr., Mechanical Engineer Mr. W. E. Brasher, Physicist

VI. SYSTEMS ENGINEERING APPROACH — Mr. W. E. Brasher

Contributing Personnel: Dr. A. E. Sobey
Mr. R. Coryell, Geophysicist

Technical editing of this report was performed by Richard E. Hohman, Ruth Wilson and Beverly Littlejohn.

The study was conducted under the cognizance of the Advanced Spacecraft Technology Division of the Manned Spacecraft Center. Mr. John Eggleston, Mr. John Dornbach and Mr. Curtis Mason periodically reviewed program progress and provided technical data and direction. Mr. Mason was contract monitor for the project.

TEXAS INSTRUMENTS INCORPORATED

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ABSTRACT

A survey of measurements, experiments and geologic studies that might be made on the lunar surface was conducted to provide the National Aeronautics and Space Administration and the scientific community with data to aid in final selection of the optimum series of experiments and observations for early APOLLO missions. Primary consideration was given experiments involving the following phenomena and properties: gravitational, magnetic, electromagnetic, and electrical fields; seismicity; planimetric and elevational position; composition and age of lunar material and geomorphic features; geochemical and geonuclear properties; rheologic and soil mechanics properties; surface geometry; temperature and thermal conductivity; stratification and density; and radiation, particle and micrometeoroid flux. The study was designed to: (1) survey lunar surface experiments that might be considered for APOLLO; (2) identify experiments that, within mission constraints, appear to be the most significant; (3) outline a tentative sequence of performance for selected experiments; and (4) provide engineering data for instruments and equipment required to perform significant experiments or studies.

Lunar surface measurements were evaluated and grouped on the basis of their contribution to five fundamental lunar problem areas: (1) hazards to the astronaut; (2) trafficability; (3) lunar basing; (4) origin, history and age of the lunar surface; and (5) origin, history and age of the earth-moon system. Although measurements from each group will be made by the astronaut on all missions, maximum emphasis during the first landing is placed on those measurements related to astronaut safety and future mission success -- and associated measurements of scientific significance. On subsequent landings, environmental hazards are still of interest, but emphasis is shifted toward more purely scientific tasks. Schedules of experiments and observations are recommended for the first three APOLLO missions. Exploration during the first mission is restricted severely by the amount of time available for on-surface activities. During longer duration missions, exploration is limited by the payload capability of the LEM. Studies are needed to determine the point of diminishing returns for increased payloads and stay time without increased astronaut range or mobility. Even on early landings, the combination of time, mobility and logistic constraints dictates obtaining geologic-geophysical data of a single-location and/or limited-time-series nature rather than conducting surveys analogous to terrestrial operations. Implanting and activating a scientific instrument package to monitor various phenomena subsequent to astronaut departure are recommended for the first and third flights. This greatly extends time-series measurements but obviously does not increase areal coverage. Equipment and instruments required for hazard analysis, geologic sampling, photography, and passive measurement of geophysical properties or phenomena comprise the bulk of early mission scientific payloads. Although subject to revision as knowledge of the moon increases, the recommendations are made with full cognizance that understanding of the lunar environment can be attained only through the

synthesis of observational and instrumental data covering several scientific disciplines.

This study identifies fundamental scientific principles and instruments appropriate for multidisciplinary lunar surface exploration. Potential measurements and experiments were evaluated sequentially on the basis of changeable factors such as knowledge of the lunar environment and technologic status. An experiment matrix was prepared and entries evaluated from the standpoint of : (1) contribution to fundamental lunar scientific or technologic problem areas; (2) solution of specific lunar problems or combination of problems; (3) engineering feasibility of conduct on the lunar surface; and (4) specific mission constraints. Data for all techniques and instruments were compiled prior to selection of instrumentation for specific missions. Thus, the study was designed not only to produce valid conclusions concerning early APOLLO missions but to provide a basic fund of scientific and instrumental data that can be re-examined simply in the light of technologic advances or mission constraint revisions.

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PART I

CHAPTER I

INTRODUCTION

A. PURPOSE AND SCOPE

The purpose of this study was to determine optimum measurements, experiments and geologic and geophysical studies to be made on the lunar surface during early APOLLO missions. An investigation of this type can be reduced to consideration of WHAT, WHY, HOW, WHERE, and WHEN, with attempts made to:

- Identify the most significant scientific and technologic experiments and studies and explain their significance. WHAT is needed and WHY is it needed?

- Determine the equipment and techniques required to make and subsequently to locate these measurements. HOW can measurements best be made and the sampling site recorded? This also includes consideration of HOW the equipment and techniques can best be utilized, i. e., should the instruments be merely activated by the astronaut and left on the lunar surface, read and recorded by the astronaut -- or both?

- Determine the best sampling sites or places for measurements. WHERE within the landing area should measurements be made, and should they be made on the lunar surface or on earth using a sample returned from the moon--or both?

- Determine which measurements should be made or experiments put into operation during the early missions. WHEN should they be made, i. e., determination of the operational sequence for conducting measurements or experiments during the APOLLO program. Consideration must be given to what data will be available if a mission does not go to completion, and the selected sequence should assure the systematic accumulation of knowledge in the various scientific disciplines of primary importance.

In making these determinations of measurements and experiments, the need and desirability of having a man on the missions must be carefully evaluated. The main concern must be to exploit man's unique capabilities fully by assuring that these capabilities are not utilized in the conduct of tasks better performed by automated devices. Man is a much more reliable data collector than complex equipment, can adapt more readily to unexpected phenomena or conditions and can contribute critical elements of judgment and discrimination in the conduct of scientific exploration. Professor Samuel Silver* has aptly pointed out that: "The interpretation of phenomena and the development of theories involve the extraction of particular classes or sets of data from the totally available data and making correlations between sets of observations and experiences. Man has the particular capability of encompassing a wide range of data, appraising it and making correlations, and the ability to recognize the unexpected and adjust his judgment and interpretations. That capability cannot be transferred to automated equipment and suffers attenuation as the distance between the experimentor and his experimental equipment is increased. Minimizing the role of man in the experiment ignores an essential element of the methodology of scientific thought."

This study was designed primarily to: (a) survey the experiments that might be considered for APOLLO, (b) identify those that, within mission constraints, appear to be most significant, (c) outline a tentative sequence for experiment conduct, and (d) provide engineering data for instruments and equipment required to perform significant experiments or studies. This information should provide NASA personnel, in conjunction with representatives from the scientific community, a firm basis for making final decisions concerning the development of experiments for early APOLLO missions.

B. GUIDES

This study was guided by a plan to conduct three APOLLO flights. The first flight consists of two alternative missions. One mission provides for one 2-hr excursion on the lunar surface devoted exclusively to scientific exploration. The alternate first-flight mission provides for two excursions, the first of 2-hr duration and the second of 2-1/2-hr duration. The second flight was considered from the standpoint of its being preceded by (1) a successful first flight (alternate one), i.e., 2 hr of scientific exploration on the lunar surface, and (2) a successful first flight (alternate 2), i.e., a total of 4-1/2 hr on the lunar surface. Both second flights consist of four excursions. The first excursion allows 2 hr on the surface devoted exclusively to scientific exploration. Scientific excursions two, three and four are each of 2-1/2 hr duration. Both second flights considered thus consist of 9-1/2 hr on the lunar surface. The third flight was considered from the standpoint of being preceded by a successful second flight (alternate 2). As on flight two, there are four excursions proposed for the third flight and a total of 9-1/2 hr expended on scientific activities on the surface.

On all flights the scientific payload is limited to 250 lb and 10 cu ft. Two 4-cu ft storage compartments are located within the LEM descent stage

*Director, Space Science Laboratory, University of California, Berkeley.

and thus subject to hard vacuum, extreme temperature, radiation, shock, and other launch, landing and environmental conditions. A 2-cu ft storage compartment is available within the LEM ascent stage and is protected from environmental hazards. A maximum of 80 lb of samples, film or recorded data can be returned to earth within this 2-cu ft compartment. Additional engineering constraints are discussed in Part II, Chapter V.

Certain assumptions were also made of priorities for broad groups of measurements, experiments and studies. Measurements to be made on the lunar surface can be grouped as those required to: (1) assure astronaut safety; (2) assure success of future missions; and (3) solve fundamental problems concerning the origin and history of the moon and solar system. Fortunately, these measurements are not mutually exclusive and many scientific measurements/observations/experiments will be, for example, significant from the standpoint of both astronaut-hazard and future-mission planning. Although measurements from all three groups will be made on all missions, the maximum emphasis for the first landing will be placed on measurements related to astronaut safety and future mission success and the scientific measurements that contribute to these fields. Subsequent missions will be directed toward monitoring some of the environmental hazards, but emphasis can be placed more on purely scientific needs.

C. CONDUCT AND RATIONALE OF THE STUDY

No fixed boundaries exist between the numerous disciplines that can be employed effectively in lunar exploration. However, there is general agreement within the scientific community that geology and geophysics will play extremely important roles. The geology and geophysics of the moon and the physical properties of lunar surface and shallow-subsurface materials are certainly major subjects for early mission study. Consequently, organization of the subject program on a task force or study group basis -- each group representing a specific earth science discipline or related technology -- is a logical approach to the problem.

Study groups were established to investigate the following:

- Field Geology*
- Geomorphology*
- Composition and Age Determination
- Geophysics*
- Special Problems (radiological, micrometeoroid, thermal)
- Soil Mechanics
- Surveying, Mapping and Photography
- Sampling Techniques
- Engineering Problems

*For simplicity and to avoid possible confusion, the prefix seleno, although technically correct, is not used to designate scientific disciplines except when reference is made to the entire lunar body, as selenodetic. Such terms as selenology, selenomorphology and selenophysics have been avoided and terminology applied to scientific disciplines on earth is used to denote lunar equivalents.

Special Problems involved disciplines not investigated by other groups and included studies by A. D. Little personnel. Engineering Problems personnel assisted other study groups in compiling general instrument information, provided detailed engineering data for high-priority instruments and studied packaging and telemetry problems.

From the standpoint of its particular discipline or technology, each study group conducted several tasks as listed in Table I-1.

TABLE I-1

LIST OF STUDY TASKS

I. IDENTIFY FUNDAMENTAL LUNAR PROBLEMS

II. COMPILE COMPREHENSIVE LIST OF MEASUREMENTS AND EXPERIMENTS THAT MIGHT BE MADE ON THE MOON

III. DETERMINE WHICH MEASUREMENTS WOULD PROVIDE THE GREATEST AMOUNT OF SCIENTIFICALLY AND TECHNOLOGICALLY SIGNIFICANT DATA

IV. COMPILE COMPREHENSIVE LIST OF INSTRUMENTS CAPABLE OF MAKING MEASUREMENTS SELECTED ABOVE

V. EVALUATE EACH INSTRUMENT TYPE ON THE BASIS OF PERFORMANCE CHARACTERISTICS AND ON THE BASIS OF POWER, VOLUME AND WEIGHT REQUIREMENTS

VI. EVALUATE EACH INSTRUMENT TYPE FOR FEASIBILITY OF OPERATION IN THE LUNAR ENVIRONMENT

VII. ASSEMBLE ALL DATA COLLECTED ABOVE IN MATRIX FORM FOR READY UTILIZATION IN THE FINAL SELECTION OF THE OPTIMUM MIX FOR LUNAR MISSIONS

VIII. RECOMMEND SEQUENTIAL ORDER IN WHICH EXPERIMENTS SHOULD BE PERFORMED AND SPECIFY THE EXPECTED WEIGHT, SIZE AND SPECIAL CHARACTERISTICS OF THE EQUIPMENT

Tasks I, II and III were primarily concerned with fundamental lunar problems of a scientific or technologic nature and measurements that would contribute to their solution. Nearly all lunar or lunar-exploration problems can be assigned to one or more of five categories or areas, i.e., properties or phenomena hazardous to the astronaut; trafficability; lunar basing; nature and age of lunar surface features; and structure, origin and history of the moon and earth-moon system. Specific problems -- whose solution would make a significant contribution within one, or preferably several, problem areas -- were identified by each study group.

This work made full use of the Sonett Committee Report, the report of the 1962 Space Science Summer Study and other NASA and Space Science Board documents. In addition, letters were sent to approximately 50 recognized authorities in the study-group disciplines and the space sciences, requesting comments concerning basic lunar problems and the most important measurements that might be made on the lunar surface during early missions. Results of this survey are presented in Appendix A.

Under Tasks II and III each group compiled a comprehensive list of measurements and experiments that might be made on the moon and which would contribute to the fund of knowledge for the specific study-group discipline. A first approximation concerning the relative importance of each measurement within each discipline also was made. Each measurement was assigned five values based on estimated significance from the standpoint of:

- Identifying or measuring properties or phenomena hazardous to the astronaut
- Determining trafficability or suitability of areas for future landing sites
- Determining the origin, nature and age of lunar surface features
- Determining the structure, origin and history of the moon and earth-moon system
- Solving problems associated with lunar basing

Measurements also were categorized, keeping in mind wherever applicable, criteria such as:

- Is a property or phenomenon being measured?
- Does the measurement require a special energy source?
- Does the property or phenomenon being measured exhibit significant vertical and/or horizontal gradations?
- Are the tests required destructive or nondestructive?
- Does the property or phenomenon change rather rapidly with time?
- If time-dependent, should the measurement be made with a Scientific Instrument Package?
- Can the measurements be made in situ without removing a sample?
- Should the sample measurement be made on the moon, on earth, or both?

Data compiled in Tasks I, II and III are included as Appendices B, C, and D and discussed in Chapters I-IV of Part II. Each of these chapters is concerned with the identification of measurements or experiments most significant in a specific discipline or technology. Determination of the relative importance of all measurements, within program and mission constraints, is discussed in Part I. For the benefit of those not planning to read the entire report, a minimum amount of repetition of pertinent material in several chapters was not deleted during editing.

Upon completion of the first three tasks, instruments or instrument types capable of making the various measurements were identified. Tasks IV, V, and VI of Table I-1 are, consequently, concerned with the requisite instrument types and their engineering and performance specifications. Instrument evaluation sheets were prepared by each study group and data concerning the following items collected for each instrument type.

- Measurand(s) (physical property, quantity or condition measured)
- Operating characteristics and dynamic range
- Weight, power and volume requirements

- Reliability
- Set-up time required
- Operation time
- Number of operators required
- Operational hazards
- State of development

Instrumentation problems are discussed in Chapter V and additional data are included in Appendices F and G.

Tasks VII and VIII involved: (a) integration of all data into a matrix form to aid in selecting optimum measurements or experiments, (b) recommendation of instruments and sequences of experiments that will assure systematic accumulation of a maximum amount of significant data, and (c) estimation of weight, size and special characteristics of instruments selected and investigation of packaging problems. These aspects of the study are discussed in Part I, Chapters II and III, and Part II, Chapters V and VI. Related material is included in Appendices E, F, and G.

The program rationale, schematically depicted in Figure I-1, dictated the previously described task sequence. A primary concept of this rationale involved progression from numerous disciplinary measurements or experiments to a few by means of successive evaluation or filtering. All possible experiments were initially compiled and subsequently evaluated from the standpoint of: (a) contribution to fundamental lunar scientific or technologic problem areas, (b) solution of specific lunar problems or combination of problems, (c) engineering feasibility of conduct on the lunar surface, and (d) specific mission constraints.

Obviously, studies could be conducted only on the basis of available data and the current status of instrumentation and pertinent technologies. The availability of data concerning the moon, the technologic status of measurement equipment and specific mission constraints were controlling factors in the subject study. As significant new lunar data become available or break throughs in exploration equipment or spacecraft technology are achieved, the conclusions reached in the program must be re-examined. Consequently, the task structure employed was designed to provide valid conclusions based not only on available data but upon the premise that re-evaluation and modification of study conclusions in the light of new data and technologic advances should be as simple as possible.

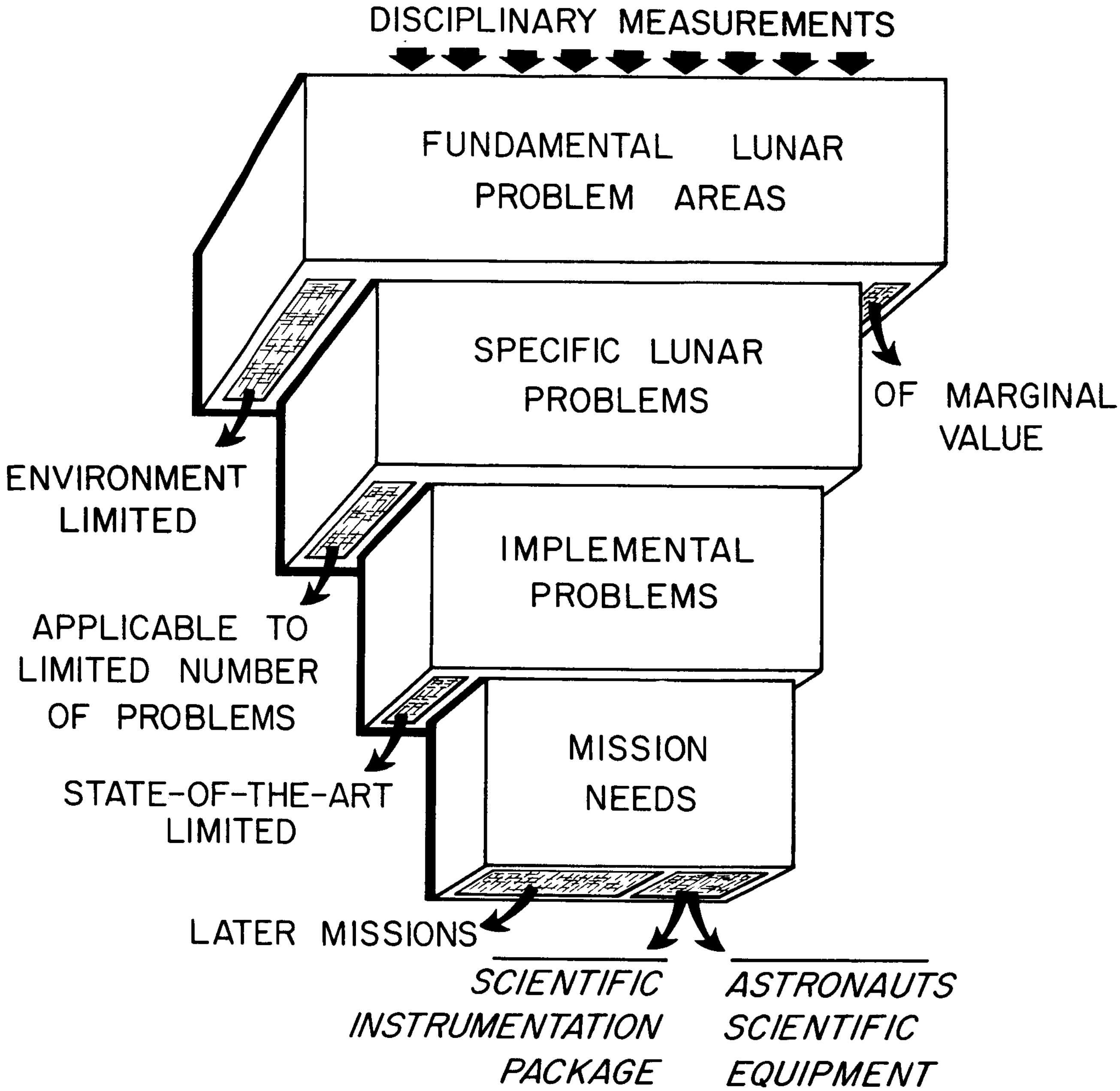

Figure I-1. Schematic of Program Rationale.

As mentioned, the basis of this design was to determine the fundamental scientific and engineering principles and instrumentation that might be used in lunar surface exploration and to perform subsequent evaluations dependent upon changing factors such as our knowledge of the lunar environment and technologic data. Data concerning all techniques and instruments have been compiled prior to selection of instrumentation for specific missions. If new inputs necessitate re-evaluation, additional information may be required for some techniques. This method, however, eliminates the possibility of having to research in detail those techniques eliminated prematurely from consideration by an initial study.

A primary objective of this study was to provide NASA and the scientific community with data that will permit final selection of experiments for early APOLLO missions. Therefore, the early-mission instrumentation and programs suggested in this report must be considered to be first approximations. The fact should be recognized, however, that considerable synthesizing and integration of multidisciplinary data have been accomplished in arriving at these suggestions. This will not be obvious to specialists in various disciplines whose "essential" experiments have not received high priority. In fact, some decisions are still only reluctantly accepted by several members of our program team. In making such decisions, however, full recognition was given the roles of both the scientific specialist and generalist.

It is axiomatic that most environmental and exploration problems will not be solved on the basis of a single discipline. It is doubtful that they will be solved by a group of specialists no matter how broad a range their talents cover, because the very nature of their training precludes total awareness of the complete range of actual environmental problems and the manner in which other disciplines impinge upon these problems. The scientific generalist or earth scientist, whose training and experience have been oriented toward employing interdisciplinary data and techniques in the solution of special problems, can serve effectively as a major contributor and catalyst. However, he can often act only as a catalyst because he cannot hope to assimilate the vast amount of knowledge available in all pertinent disciplines. In addition, he must appreciate fully the engineering and other mission constraints before valid recommendations can be made. The study described in this report was based on these concepts.

CHAPTER II

RECOMMENDATIONS

A. MISSION SCHEDULES

1. Summary

Recommended schedules of scientific instruments and observations for the first three APOLLO flights are presented in this section. A committee of senior workers on the APOLLO contract compiled the schedules on the basis of information collected by the various study groups during the course of the contract. The study groups provided data on all feasible lunar experiments and measurements and on the scientific apparatus necessary to perform them. Possible hazards to the astronauts received first priority. Hazard measurements, therefore, are recommended at the beginning of the first excursion for all three flights, since hazards absent at the first landing location may possibly be important at the second and third sites. There was little need to weigh priorities among the different hazard observations; all that had been seriously proposed were included.

Measurements and experiments not involving hazards are scheduled next in the order of their general scientific interest. Emphasis was placed on those yielding information bearing on the widest range of questions and those providing better results when performed on a manned rather than an unmanned mission. Limitations of weight and time proved to be more severe than those of volume, since the instruments recommended can be miniaturized. On the first flight, the limiting factor is time; on the second and third, it is weight. Thus, the astronaut will be able to do comparatively little observation and exploration on the first flight. Even though a greater time allowance is provided on the second and third flights, he will be unable to go more than about 1000 ft from the LEM because of the anticipated low walking speed.

In accordance with NASA's requirements, two alternative programs or "profiles" for the first two flights were considered. Flight programs are summarized in Figure II-1. Alternative I provides for a single excursion on the first flight, whereas Alternative II provides for two excursions. The present study indicates that first-flight Alternative I constitutes a mission of marginal value since there is insufficient time for conducting observations and experiments. Alternative II of the first flight, if it proves feasible, is clearly the more desirable. The second flight consists of a group of four excursions that differ according to which alternative is selected for the first flight.

In the second flight, the geophysical instrument package, with its large weight requirements, will be replaced by a sampling drill and various devices for measuring electrical, optical and chemical properties of the

	ALTERNATIVE I	ALTERNATIVE II
FIRST FLIGHT	EXCURSION 1, 120 MIN See Table II-2	EXCURSION 1, 120 MIN See Table II-3
	NO SECOND EXCURSION	EXCURSION 2, 150 MIN See Table II-3
SECOND FLIGHT	EXCURSION 1, 120 MIN See Table II-4	EXCURSION 1, 120 MIN See Table II-4
	EXCURSION 2, 150 MIN See Table II-5	EXCURSION 2, 150 MIN See Table II-6
	EXCURSION 3, 150 MIN See Table II-7	EXCURSION 3, 150 MIN See Table II-8
	EXCURSION 4, 150 MIN See Table II-9	EXCURSION 4, 150 MIN See Table II-9
THIRD FLIGHT		See Table II-10

Figure II-1. Programs for Flights 1, 2 and 3 of APOLLO Missions.

lunar surface and material. However, if the first-flight measurements of seismicity, tidal gravity and lunar magnetism give unexpected or unexplainable results, it may be desirable to repeat them at the expense of some of the other recommended observations. Weight and volume requirements for Alternatives I and II of the first and second flights and for the third flight are summarized in Table II-1.

On the third flight a scientific instrument package is recommended for time-series measurements considered important but not included on the first flight. On subsequent flights, measurements which receive high ratings in the computer evaluation program are listed in an approximate order of preference.

The later excursions allow many minutes for walking and for visual observation of geologic forms and structure. For this reason, it is imperative that the astronaut be well trained in field geologic techniques.

TABLE II-1

SUMMARY OF WEIGHT AND VOLUME REQUIREMENTS FOR FIRST, SECOND AND THIRD APOLLO FLIGHTS

	Lb	$In.^3$
FIRST FLIGHT SUMMARIES		
Alternative I*		
Instruments and equipment	207.4	6,423
Packaging and thermal control	41.5	1,605
Total	248.9	8,028
Alternative II**		
Instruments and equipment	208.6	12,782
Packaging and thermal control	41.7	3,196
Total	250.3	15,978
SECOND FLIGHT SUMMARIES		
Alternative I		
Instruments and equipment	207.0	7,546
Packaging and thermal control	41.4	1,886
Total	248.4	9,432
Alternative II		
Instruments and equipment	207.3	7,563
Packaging and thermal control	41.5	1,891
Total	248.8	9,454
THIRD FLIGHT SUMMARIES		
Instruments and equipment	208.5	6,526
Packaging and thermal control	41.7	1,632
Total	250.2	8,158

*Power supply -- battery pack/solar cell array
**Radioisotope power supply

Land forms reflect the history and composition of the materials that comprise them in a manner highly diagnostic to an experienced observer and, considering the brief time available, such information could not be acquired by a person without appropriate training.

The recommended schedules, of course, are based on current knowledge of the moon and are subject to modification as new data are acquired--whether prior to landing, on unmanned missions or on the first manned missions. For example, in the last category, if the astronaut discovers on his first excursion that portions of the lunar surface will not bear his weight, he will be obliged to modify the program immediately. Furthermore, the program for the second flight unquestionably will be considerably altered by the findings of the first. The recommendations, especially those for the second flight, must be regarded as a sample, showing what can be done in certain assumed circumstances rather than what will be undertaken eventually.

2. First Flight

a. Alternative I (One Excursion)

1) Time Distribution

Alternative I of the first flight permits a single excursion of 2 hr for scientific purposes. The program is outlined in Table II-2, giving experiments in the order in which they are to be performed and an estimate of the time required for each. Only estimates are provided; a systematic time and motion study is beyond the scope of this report, and the total time allocated to perform certain observations such as those made with the boot thermometer and staff penetrometer will be expended at numerous intervals during the excursion. The general distribution of allotted time is 28 min for investigation of immediate hazards, 25 min for emplacement and operation of scientific instruments, 37 min for sampling and geologic studies, 15 min for visual observations, and 15 min for nonassignable walking.

2) Hazards

Measurement of hazards has the highest priority on both the first and second flight. The primary hazard is now believed to be radiation. This will be monitored by personal dosimeters and survey rate meters, one in the LEM and one to be left on the moon to transmit readings. Micrometeoroid infall and secondary ejecta may constitute a hazard to the astronauts, but these phenomena can be evaluated by visual observation of surface impacts and by sound when they strike the LEM. These observations will not permit an estimate of the momenta and mass involved and although utilization of a specially designed micrometeoroid and ejecta flux sensor is highly desirable,

TABLE II-2

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS PROPOSED FOR EXCURSION 1, ALTERNATIVE I, FIRST FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1 P. V-11	Text Discussion Part II (Chap. & Page)
6.0	230		Descent camera	70	V-51
3.0	320		Descent camera printer (pre-egress)	71	IV-58
0.6	2		Personal dosimeters (2)	34	V-32
1.0	70	5	LEM survey rate meter	30	V-31
0.5	4	2	Landing gear thermometer	50,51	V-40,41
0.5	17	10	Chemical reactivity detector	33	V-32
0.5	4	2	Boot thermometer	53,54	V-40,41
5.3	90		Camera and flash	68,69	V-51
2.5	20	4	Staff penetrometer	4,74	I-34
4.5	150	0	Tracking transducer	64	V-47,48
7.0	450	5	Gravity meter	34	V-39
157.1	4742	20	Scientific Instrument Package (SIP)		V-53 to 71
			Survey rate meter	30	V-31
			Transponder	72	
			Combination seismometer	45	V-45
			Helium magnetometer	39	V-38
1.2	28	5	Sample culture pH readout	27	V-29
10.7	250	19	Sampling (6 vac., 26 bags)	81	IV-24
7.0	46	18	Geology		I-32,33
		15	Visual observation		
		15	Walking (nonassignable)		
207.4	6423	120	Totals		

results of preliminary studies indicate that instrument weight is excessive for the first flight. The hazard presented by fine-grained surficial material either because of great thickness or adverse electrical behavior will be tested both by observation of penetration by the LEM landing gear and by the astronaut during his egress. Samples will be collected immediately to test for chemical reactivity and possible biologic content. Temperature recording devices in the LEM legs and in the astronaut's boots will warn against unexpected thermal hazards.

Next in importance is probably the mechanical condition of the surface. It is thought that really valid data on this hazard will not be obtained until the surface is tested manually with a staff or staff penetrometer. The fundamental decision of whether the surface near the LEM is safe for traverse by a man in a space suit depends on such surface characteristics as bearing strength, adhesion or bonding of surficial particles, roughness, and the presence of voids and crevasses. This decision must be made by the astronaut as he leaves the LEM. It will be based on personal judgment and observations made of penetration by the LEM landing gear and staff penetrometer in the first few minutes during and after egress. The decision, of course, will be complicated by the fact that data observed in one spot or even one locality may not be representative and that, until much experience is gained, the trafficability of the lunar surface can not be adequately assessed.

3) Sampling and Geology

Sample collection is the most important scientific activity in the first flight. The goal is to locate and recover samples illustrating material differences, but the determinations will have to be made by visual inspection and will be handicapped by light conditions and the need for obtaining samples outside the area contaminated by the landing blast. Sampling tool packages to be carried on this and subsequent flights are tabulated on p. IV-24 to 26. If the rock in the accessible area appears homogeneous, the problem will be to determine differences; if a wide variety of rock types is observed, the problem will be to choose representative types. Thus, the astronaut will be required to make quick decisions, with few rules except geological intuition for guidance. Any geological activity undertaken, such as recognizing modifying processes, indentifying rocks and taking pictures, must be combined with sampling as it will provide criteria for sample selection. A geology kit will be carried on all flights (refer to p. I-23), and coupled with the contents of the sampling package, will provide the necessary equipment for sampling requirements and geologic observations.

4) Scientific Instrument Package

Geophysical information is to be acquired by emplacing an assembly or package of scientific instruments and leaving it on the moon to transmit data. Utilization of a single instrument package or container will permit use of a common transmitting system and reduce the time required to install and initiate instrument operation. The recommended package for Alternative I of the first flight consists of a survey rate meter, a helium magnetometer, a combination long- and short-period seismometer and recording gravity meter, and a transponder. Power necessary for thermal control and transmission of the data brings the weight of the package nearly to the maximum allowable. A detailed discussion of shielding and transmission requirements is presented in Part II, Chapter V. Deductions to be made from the observations are fundamental to both engineering and scientific knowledge of the moon. Therefore, it was judged that the instrument package has sufficient priority to be included in the first flight. In addition, the excursion time is so short that it is economical to set up recording instruments that make minimum demands on astronaut time.

A portable gravity meter for determining absolute gravity (not now feasible with the recording meter) is not included in the instrument package but will be carried to various points on the lunar surface by the astronaut. If the LEM is steady, the meter can be read inside. On later missions, it could be used to detect local seismicity as well as local gravity anomalies.

5) Visual Observation, Walking

It is estimated that in 30 min of walking, which includes time spent in visual observation, the astronaut will be able to undertake a round trip to a point approximately 500 ft from the LEM. At least some time while walking will be spent in observation of land forms, stratigraphy, rock types, surface roughness, and structure, so the walking period in the recommended program has arbitrarily been divided evenly between walking and observation.

b. Alternative II (Two Excursions)

Alternative II of the first flight consists of two excursions, the first of 2 hr (as in Alternative I) and a second excursion lasting 150 min. Table II-3 is a detailed tabulation of equipment requirements and weight, volume and time allotments for both excursions.

The first excursion of the second alternative does not differ from that of the first alternative, except for the deletion of the gravity meter. Time assigned for gravity meter measurements (5 min) was reallocated to sampling.

In the second excursion of the second alternative, the following items are added to the schedule:

TABLE II-3

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS PROPOSED FOR EXCURSIONS 1 AND 2 OF ALTERNATIVE II, FIRST FLIGHT

Lb	In.^{3}	Min	EXCURSION 1	Instrument Entry on Table V-1 P. V-11	Text Discussion Part II (Chap. & Page)
6.0	230		Descent camera	70	V-51
3.0	320		Descent camera printer (pre-egress)	71	IV-58
0.6	2		Personal dosimeters (2)	34	V-32
1.0	70	5	LEM survey rate meter	30	V-31
0.5	4	2	Landing gear thermometer	50,51	V-40,41
0.5	17	10	Chemical reactivity detector	33	V-32
0.5	4	2	Boot thermometer	53,54	V-40,41
5.3	90		Camera and flash	68,69	V-51
1.8	24		extra film and flash attachment battery	69	
2.5	20	4	Staff penetrometer	4,74	I-34
4.5	150		Tracking transducer	64	V-47,48
152.7	11,286	20	Scientific Instrument Package (SIP)		V-53 to 71
			Survey rate meter	30	V-31
			Transponder	72	
			Combination seismometer	45	V-45
			Helium magnetometer	39	V-38
			Surface temperature loop (1)	54	V-40, 41
			Thermal conductivity probe	56,57	V-41,42
1.2	28	5	Sample culture pH readout	27	V-29
12.8	323	24	Sampling (5 vac., 2 mech. struct. containers, 24 bags).	82	IV-25
7.0	46	18	Geology		I-32,33
		15	Visual observation		
		15	Walking (nonassignable)		
199.9	12,614	120	Total Excursion 1		
			EXCURSION 2		
8.0	150	15	Reflectance radiometer	59	V-59
0.7	18	10	Susceptibility bridge	37	V-36
		12	Surface temperature loop	54	V-40,41
		5	Thermal conductivity probe	27	V-29
		20	Sampling	82	IV-25
		28	Geology		I-32,33
		30	Visual observation		
		30	Walking (nonassignable)		
8.7	168	150	Total Excursion 2		
208.6	12,782	270	Total Flight 1, Alternative II		

- Scientific Instrument Package

  Surface temperature loop
  Thermal conductivity probe
  Surface reflectance measurement
  In situ magnetic susceptibility measurement

- A 1-hr walking and observation traverse
- 48 min for sampling and geology

The extra time for sampling and geology compensates for the lack of sampling and geologic observation time imposed by constraints in the first excursion and provides for a better balanced mission. Acquisition of detailed knowledge of the lunar surface is important in planning the second flight but, because of the high priority of the scientific instrument package, the single-egress flight (Alternative I) does not allow detailed observation of the surface. See Part II, Chapter V, for further discussion.

3. Second Flight

a. Plan and Constraints

The second flight consists of four excursions--the first of 120 min and the latter three, 150 min each. Schedules for the excursions differ according to which alternative is selected for the first flight. For the second flight, considerably more time is available, volumes are well under the limit and power requirements are relatively small.

The second flight differs from the first principally because alternatives are scheduled based on decisions of the astronaut after he arrives and examines the terrain. More will be known about the lunar terrain after the first flight, and the recommendations may be modified accordingly. However, based on present knowledge, it seems unrealistic to develop programs for the third and fourth egresses without recommending possible modifications dependent on the character of the surface.

b. First Excursion

1) Hazards

The schedule (Table II-4) recommended for observation of hazards on the first excursion of the second flight is the same as for the first excursion of the first flight. This procedure is suggested because it should not be assumed (in the current stage of lunar exploration) that certain hazards,

TABLE II-4

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR EXCURSION 1, ALTERNATIVES I AND II, SECOND FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1, P. V-11	Text Discussion Part II (Chap. & Page)
6.0	230		Descent camera	70	V-51
3.0	320		Descent camera printer (pre-egress)	71	IV-58
0.6	2		Personal dosimeters (2)	34	V-32
1.0	70	5	LEM survey rate meter	30	V-31
0.5	4	2	Landing gear thermometer	50,51	V-40,41
0.5	17	10	Chemical reactivity detector	33	V-32
0.5	4	2	Boot thermometer	53,54	V-40,41
5.3	90		Camera and flash	68,69	V-51
3.8	64		extra film and flash attachment battery	68,69	
2.5	20	4	Staff penetrometer	4,74	I-34
4.5	150		Tracking transducer	64	V-47,48
7.0	450	5	Gravity meter	34	V-39
1.2	28	5	Sample culture pH readout	27	V-29
51.1	1019	29	Sampling (8 vac., 2 mech. structure, 22 bags)	83	IV-26
7.0	46	28	Geology		I-32,33
		15	Visual observation		
		15	Walking (nonassignable)		
94.5	2514	120	Total		

if absent or unimportant in one locality, will be absent or unimportant everywhere. Clearly, the recommended schedule of hazard observations for the second flight should be reviewed thoroughly in the light of the findings of the first. These certainly will indicate an order of importance for the hazards that were anticipated and perhaps introduce others that were not expected. According to the recommended schedule, hazard observations will require 28 min.

2) Scientific Measurements

Emphasis is placed on geologic and sampling operations in the first excursion, and measurements with scientific instruments are confined to a reading of a gravity meter. This position was adopted because, in subsequent excursions, observations will be made and experiments performed which depend for their effectiveness on their relation to the local terrain. Visual observations, sampling and geologic operations, therefore, will be undertaken with a view to planning the measurements and experiments scheduled for the later excursions.

c. Second Excursion

The second excursions are devoted largely to scientific and engineering measurements. These are listed in the schedule (Tables II-5 and II-6) and their utility discussed in the appropriate chapters in the body of the report. They involve the use of various instruments in measuring the physical, chemical and mechanical properties of lunar materials and, if desired, could be repeated for more samples and locations than are in the present schedule.

d. Third and Fourth Excursions

The third and fourth excursions are devoted primarily to geological, geophysical and compositional observations allocated on the basis of the character of the lunar surface. Instruments selected for these observations are shown in Tables II-7, II-8 and II-9. Several different sets of lunar surface conditions have been envisioned as possibilities. Four examples follow.

(1) Relatively smooth rock surfaces with thin cover of dust and rubble, and fairly homogeneous material within astronaut's walking radius (type of surface sought for a landing site)

(2) Unsorted rubble and dust of unknown thickness overlying bedrock; small-scale land forms not numerous

TABLE II-5

WEIGHT, VOLUME AND TIME REQUIREMENTS
FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS
FOR EXCURSION 2, ALTERNATIVE I, SECOND FLIGHT

Lb	$In.^3$	Min		Instrument Entry on Table V-1, P. V-11	Text Discussion Part II (Chap. & Page)
17.6	1200	15	X-ray diffractometer (3 samples)	11	V-19
2.0	40	10	Probe dielectrometer	*	
6.0	40	5	Vane shear tester	78	V-52
9.0	120	10	Kreisman gauge	26	V-28
13.2	690	15	Gas chromatograph	20	V-25
10.0	860	10	Differential thermal analyzer	13	V-20
8.0	150	15	Reflectance radiometer	59	V-59
0.7	18	10	Susceptibility bridge	37	V-36
0.4	4	10	Thermal conductivity probe	56,57	V-41,42
		25	Visual observation		
		25	Walking		
66.9	3122	150	Total		

*Entry 7, Appendix D, p. D-21.

TABLE II-6

WEIGHT, VOLUME AND TIME REQUIREMENTS
FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS
FOR EXCURSION 2, ALTERNATIVE II, SECOND FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1 P. V-11	Text Discussion Part II (Chap. & Page)
17.6	1200	15	X-ray diffractometer (3 samples)	11	V-19
2.0	40	10	Probe dielectrometer	*	
6.0	40	5	Vane shear tester	78	V-52
9.0	120	10	Kreisman gauge	26	V-28
13.2	690	15	Gas chromatograph	20	V-25
10.0	860	10	Differential thermal analyzer	13	V-20
1.0	35	10	Erosion particle movement sampler	8	V-18
		15	Sampling		
		20	Geology		
		20	Visual Observation		
		20	Walking		
58.8	2985	150	Total		

*Entry 7, Appendix D, p. D-21.

TABLE II-7

WEIGHT, VOLUME AND TIME REQUIREMENTS
FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS
FOR EXCURSION 3, ALTERNATIVE I, SECOND FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1, P. V-11	Text Discussion Part II (Chap. & Page)
5.0	430		Gravity gradiometer	44	II-11, 12
3.6	690		Tripod for surveying camera	63	
5.0	140		Portable magnetometer	38, 39	V-38
		60	Gravity traverses*		II-6, 7
		10	Sampling		
		15	Geology and visual observation		
		65	Walking		
13.6	1260	150	Total		

*If terrain is rough and land form units complex, eliminate gravity traverses and devote additional 55 min to geology and visual observation.

TABLE II-8

WEIGHT, VOLUME AND TIME REQUIREMENTS
FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS
FOR EXCURSION 3, ALTERNATIVE II, SECOND FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1 P. V-11	Text Discussion Part II (Chap. & Page)
5.0	430		Gravity gradiometer	44	II-11, 12
3.6	690		Tripod for surveying camera	63	
5.0	140		Portable magnetometer	38, 39	V-38
8.0	150	15	Reflectance radiometer	59	V-59
0.4	4	10	Thermal conductivity probe	56, 57	V-41, 42
		55	Gravity traverses		II-6, 7
		10	Sampling		
		15	Geology and visual observations		
		45	Walking		
22.0	1414	150	Total		

(3) Terrain irregular; small-scale land forms (prominences, depressions, fissures, etc.) visible through cover

(4) Material and land forms highly differentiated

At present, it is impossible to estimate which of the examples is the most likely to be descriptive of the surface. The uncertainty inherent in available knowledge is illustrated by the fact that the ocular limit of resolution for detail on the lunar surface is now about the same as the astronaut's walking radius. This means that objects now visible are too large to be traversed by the astronaut; and, conversely, the objects he will be able to encompass in his traverses are too small to be noted by telescopic observations. Presumably, the findings of the first mission will do much to indicate which of the above descriptions most nearly resembles the lunar surface. A smooth and monotonous surface suggests geophysical experiments; a complicated terrain suggests geological observations; differentiated and heterogenous material suggests compositional determinations as well as geology.

1) Geophysical Experiments

The best LEM touchdown site will be much like the area described in the preceding example 1. If the surface is smooth and monotonous, geological and compositional studies which can be undertaken within the walking range of the astronaut will not be especially rewarding, so geophysical experiments will be appropriate. The simplest of these would be to read the gravity meter at intervals of 50 ft in two traverses (at right angles to each other) that cross the area within range of the astronaut. The observed gradients would provide a clue to broad subsurface trends and possibly the deflection of the vertical. Local anomalies would be evidence of shallow structure. Elevations and locations of stations would be determined by surveying camera and tracking television with procedures developed fully in Section C of Chapter IV.

Where the surface is covered with a layer of rubble (example 2 of the preceding), it is desirable to know what is underneath. If the surface were regular enough, gravity would give some indication of differences in the depth of the cover but little knowledge of the character of the bedrock. A portable seismograph system, such as is used for foundation engineering, would show the existence and attitude of bedrock and its compressional velocity which might provide evidence of its composition.

If the moon has a magnetic field, a magnetometer traverse should be made at intervals similar to those used for the gravity survey. This can be undertaken in connection with either the seismic line or the gravity traverse to see whether the subsurface exhibits variations in magnetic susceptibility. This again would be a clue to the character of the hidden subsurface.

TABLE II-9

TIME ALLOTMENTS AND ADDITIONAL INSTRUMENTS AND EXPERIMENTS PROVIDED FOR EXCURSION 4, ALTERNATIVES I AND II, SECOND FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1, P. V-11.	Text Discussion Part II (Chap. & Page)
32	650	65	Refraction seismic system*	49	V-39
		5	Sampling		
		15	Geology and visual observation		
		65	Walking		
32	650	150	Total		

*If land forms are well defined, reduce seismic traverses to 15 min and increase sampling to 30 min and geology and visual observation to 40.

2) Geological Observations

If, contrary to expectation, the surface at the landing site proves to be irregular, an investigation of the land forms by geological methods will yield more knowledge than subsurface exploration of the short-range type recommended. Any evidence of stratification, structure and variation in rock types that can be gathered will be of immediate importance. Geomorphic observations of land form shape, size, orientation, and composition should be made and evidence of modifying processes sought. The importance of lava tubes, small craters, fissures, and similar features to lunar basing is discussed in Chapter II, Part II, of this report.

3) Compositional Determinations

If heterogeneity in the rocks is observed, it will be important to collect as many samples as possible and to describe as far as possible their physical properties and field relationships.

4. Third Flight

a. Plan and Constraints

The decision to include on any mission schedule scientific measurements that involve acquisition of time-series data over a period longer than the astronaut's stay on the lunar surface automatically imposes a payload penalty for the concomitant telemetry system with its power supply.

The most critical aspect of this payload penalty is the weight of these components, which may range from approximately 100 to 150 lb depending on the nature of the measurement involved. Weight which can be allotted to instruments or equipment to be used by the astronaut while on the lunar surface is thus severely limited.

These factors lead to the conclusion that an increased weight allotment for scientific instruments and equipment should receive serious consideration in order that maximum return is realized in exchange for the penalty paid to obtain scientific data over extended periods of time. If all such measurements were concentrated on a single flight, it may be possible to effect a trade-off in life-support for two or more excursions for the increased weight required. Flights with four or more excursions would then be limited to instruments and equipment for measurements that can be made by the astronaut while on the moon and for extensive geologic observation and study. Even a flight devoted primarily to emplacement of a versatile SIP should, however, allow the time and means to obtain the maximum weight in surface samples that can be returned to earth.

Consideration might also be given to the provision of a heavier and more elaborate drill so that holes of greater depth may be made, both for scientific probes with certain SIP instruments and for the recovery of more extensive subsurface samples. Practicality of including the drill in the third flight is in part dependent on weight restrictions and on the amount and character of data obtained on earlier flights. The heavy drill is not recommended for the flight because its use does not now appear feasible. However, the problem should be reconsidered after the second flight has been completed.

b. Recommendations

Recommendations for the third APOLLO flight are intended to provide for possible time-series measurements considered important but not included on the first flight. On Table II-10 a detailed tabulation is presented of the components of the SIP package and for other instruments proposed for the third flight. Weight, volume and time allotments and text references to the instruments are also shown on Table II-10.

5. Subsequent Flights

Drastic limitations are placed on APOLLO missions by the 250 lb weight restriction. If a scientific instrument package is included, as much as 60 per cent of the weight must be allotted to SIP package telemetry and power requirements and 20 per cent to thermal control and packaging. It is hoped that by the time of the fourth flight a greater payload can be achieved for APOLLO missions.

Instruments and measurements for missions following the third flight are listed on Table II-11 in an approximate order of preference.

TABLE II-10

WEIGHT, VOLUME AND TIME REQUIREMENTS FOR MEASUREMENTS, OBSERVATIONS AND EXPERIMENTS PROPOSED FOR THIRD FLIGHT

Lb	In.^{3}	Min		Instrument Entry on Table V-1, P. V-11.	Text Discussion Part II (Chap. & Page)
9.0	550	0	Descent camera and printer	70	V-51
0.6	2	0	Personal dosimeter (2)	34	V-32
0.5	4	2	Landing gear thermometer	50,51	V-40,41
0.5	4	2	Boot thermometer	53,54	V-40,41
9.1	154		Camera, flash (extra film and battery)	68,69	V-51
2.5	20	4	Staff penetrometer	4,74	I-34
4.5	150		Tracking transducer	64	V-47,48
7.0	450	5	Gravity meter	34	V-29
111.7	4067	122	Scientific Instrument Package (SIP)		V-66
			Line source pressure gauge	62	V-47
			Thermal conductivity probe	54	V-41
			Micrometeoroid flux and ejecta detector	35	V-32 to 36
			Radiometric heat flux meter	61	V-45 to 47
			Surface temperature loop	54	V-40,41
51.1	1019	40	Sampling package (8 vac., 2 mech., 22 bags) & flexible drill	83	IV-26
5.0	60		Power pack for hand drill		
7.0	46	55	Geology kit		I-32,33
		15	Visual observation		
		25	Walking, nonassignable		
208.5	6526	270	Totals		

TABLE II-11

MEASUREMENTS AND INSTRUMENTS RECOMMENDED FOR MISSIONS FOLLOWING THE THIRD FLIGHT

Instrument	Measurement(s)	Instrument Entry on Table V-1, P. V-11	Test Discussion, Part II, (Chap.& Page)
Surveyor soil mechanics device	Shear strength, bearing strength	76	V-51
Thermal conductivity probe (LEM landing gear)	Landing site surface thermal conductivity	57	V-41, 42
Modified flash radiometer	Surface thermal diffusivity	58	V-42, 43
Charged dust detector	Electrostatics	41	V-38
Gamma ray spectrometer	Chemical composition Radioisotope composition Lunar radioactivity Secondary radiation	23	V-27, 28
Line source pressure gauge	Surface interstitial gas pressure	62	V-47
X-ray spectrometer	Analytical Instruments	14	V-21
UV-visible spectrometer	(Two or three should be chosen for sample analysis on lunar surface)	16	V-22
Neutron activation analyzer		17	V-22, 23
Alpha scattering spectrometer		18	V-23
Neutron scattering spectrometer		19	V-24, 25
Mass spectrometer		21-22	V-25 to 27
Portable survey rate meter with directional capabilities	Lunar radioactivity, secondary radiation	32	I-120
Harvard miniature soil compaction apparatus	Soil compaction	77	III-26
Direct shear tester, flexible tool with all components	Soil shear strength	79	
Theodolite with tripod	Position of LEM by resection	63	
AC/dc, pulse current sources; with 4 electrodes, voltmeter, cables	Resistivity in situ (active), anisotropy in resistivity, electrical transients in situ	40*	V-38
Solar plasma spectrometer	Solar wind, particulate radiation flux	29**	V-30, 31
Particle spectrometer	Solar flares, particulate radiation flux	31**	V-31, 32
Particle spectrometer and TI low-field helium magnetometer	Cosmic rays with magnetometer	31, 39**	V-31, 32, 38
Cal-Tech portable seismic system	Induced seismic motion	49	V-39, 40
Vane shear tester	Shear strength	78	V-52
Soil sampling tube (in sampling package)	Soil density		IV-22
Heavy sampling package	Inclusion of core samples		

*SIP measurements. Should be undertaken on first or third flights if weight allotment is increased.

**Also refer to entries 46 and 47, p. F-6, Appendix F.

B. GENERAL COMMENTS

The primary conclusions and recommendations resulting from the study are incorporated in the previously described mission schedules and in Chapters I through VI of Part II. However, some general comments are in order.

As previously indicated, time limitations are the main reason for the marginal value of a 2-hr lunar surface excursion (Alternative I of the first flight). Alternative II (4-1/2 hr of scientific excursion time) of the first flight is therefore preferred. The second flight excursions are restricted by payload weight limitations thus indicating the desirability of investigating the scientific potential of a Stay-Time Extension Module (STEM). A major aim of such an investigation would be to determine the trade-off point at which increased payloads and stay time would bring diminishing returns without increased astronaut mobility or range. Even on the early landings considered in this study, the combination of time, mobility and logistic constraints dictates that emphasis be placed on obtaining geological-geophysical data of a single-location and/or limited-time-series nature rather than conducting more conventional areal surveys. The Scientific Instrumentation Package (SIP) permits extension of time series measurements but does not increase areal coverage. The SIP packages are limited in size and scientific utility by power, telemetry and thermal control requirements. An increased payload for APOLLO missions is desirable to permit more extensive utilization of SIP packages.

A series of time and mobility check tests should be conducted on earth by the astronauts on the various mission schedules discussed in the preceding section. These will permit more accurate estimates of time requirements and mobility-range capabilities. Tests should be conducted in space suits and within terrestrial geologic environments similar to those expected on the lunar surface.

Instruments recommended for the first, second and third flights should be developed and tested. The importance of instruments for making hazard measurements, acquiring samples and obtaining descent and on-surface photographs has been stressed, but development programs for all recommended items should begin immediately. Most of these instruments will require extreme design modification, and development should be accomplished within the next 2 yr if the devices are to be qualified for flight by early 1969. Design improvements must be made to decrease weight, power and volume requirements of scientific and telemetry equipment. Weight and volume requirements and heat generation of power supply equipment should be reduced. Instrument tests should be performed under simulated lunar environmental conditions with emphasis on instrument reliability, repeatability and portability as well as ease of astronaut manipulation. Close coordination is essential between groups responsible for the engineering design of the LEM and those concerned with scientific instrumentation.

In view of the importance of acquiring lunar surface samples, additional studies should be made to design valid sampling programs for a variety of possible lunar surface conditions. Detailed studies also should be made of the effect of the LEM landing operations on static and dynamic physical, chemical and radiologic properties of materials in the touchdown area. The significance of these effects on the scientific observations, measurements and instrumentation recommended in the mission schedules and on the sampling programs should be determined. If these effects invalidate certain types of data to be obtained under the recommended schedules, modified schedules must be prepared. Samples returned to earth should be examined and tested initially in a simulated lunar pressure and temperature environment. This will require the development of special techniques and facilities for sample handling and testing. Studies should be initiated to design lunar sample testing facilities and programs. Experience gained from dummy sample testing techniques will minimize the possibility of damage during subsequent testing of lunar samples. Although the probability of their existence is remote, sampling techniques should provide for testing near surface zones for life forms.

The more that is known about the moon and cislunar environment prior to APOLLO landings, the greater the probability of technical and scientific success. The broad range of unmanned and earth-based programs being conducted by NASA takes full cognizance of this fact. Among the earth-based programs, those involving geophysics, physical property determination and remote sensing might receive more emphasis because of their special value in providing scientific backup for early APOLLO landings. Based on field surveys and laboratory studies, diagnostic geophysical criteria should be developed to distinguish between meteoritic and volcanic origin of selected geologic features. Additional emphasis should be given to determining the physical properties of various materials, possibly found on the moon, under full lunar-day temperature and pressure ranges. Under lunar environmental conditions, physical properties of rocks and minerals may well exhibit values not correlative with terrestrial counterparts. Areal extrapolation of data obtained at a lunar landing site can be accomplished only within a framework provided by photographs or imagery obtained by remote sensing systems. It is extremely important, therefore, that the effects of resolution, scalar and other changes on the interpretation of terrestrial aerial and satellite photography be thoroughly understood.

In a more general vein, administrative provisions should be made for periodic formal reviews of advances in scientific instrumentation, data acquisition, sampling techniques, solar flare prediction, micrometeoroid flux determination, and other fields of special pertinence to the APOLLO program. The need for a comprehensive biological and medical program to determine the effect of lunar and cislunar environments on man cannot be overemphasized.

A great variety of instruments, ranging from simple to complex, has been considered and a select number recommended for the early APOLLO flights. Instrument selection was based in part on the fact that a man-instrument team can yield results of more far-reaching value than can instruments alone. This stems from such factors as: (1) the unique flexibility of man's mental and physical capabilities, (2) his ability to ask as well as answer questions and (3) his ability to make decisions from a combination of stored and immediately observable data. In short, only man can intelligently set up, operate, monitor, program, reprogram, and service instruments--and simultaneously make decisions and judgments as the situation demands. Perhaps the best analogy is that of a medical examination where all types of instruments are used, but the doctor synthesizes the information and makes the necessary decisions after analyzing and evaluating instrumental and visual data. In the earth sciences, the ability to synthesize instrumental data with visual or field observations is also a basic requirement. This must be recognized in planning each APOLLO mission and reasonable time allocations made for acquiring both observational and instrumental data. The desirability of utilizing instruments to measure time-variable phenomena for a period greater than the on-surface stay time of the LEM is widely recognized. Areally varying properties or phenomena, however, must be measured or observed by a roving astronaut. The problem thus involves the allocation of astronaut time (remaining after set-up and activation of the scientific instrumentation for time-series measurements) between observational and instrumental tasks. The importance of obtaining observational data cannot be overemphasized, yet the alien nature of the lunar environment and its possible psychologic and physiologic effects would also seem to recommend the performance of numerous, fairly simple mechanical tasks during the first landing. Certainly, reasoning and deductive processes will be more reliable and important on subsequent flights, i.e., after an appreciation of the lunar environment has been gained. Man tends to filter or synthesize data when recording information either observationally or instrumentally acquired. While this capabilaity is a tremendous advantage in many exploration activities, it is questionable as to whether this filter should be employed extensively until first-hand knowledge of the lunar surface is available from the initial landing. During the initial landing it would appear that a maximum amount of raw data should be obtained. This can be accomplished effectively by instruments, but the astronaut must activate the instruments and judiciously select sampling sites so that reliable and truly representative data can be acquired. The importance assigned to observational versus instrumental data gathering will, of course, change from mission to mission and is dependent upon a variety of factors. Consideration must be given the scientific training of the astronaut, mission purpose, probable landing site conditions and a myriad of mission constraints and prior mission results. Nevertheless, regardless of the type of data acquisition emphasized, the presence on the lunar surface of an experienced professional geologist with a thorough understanding of vacuum physics and hypervelocity impact phenomena would be highly desirable. As soon as in-flight considerations permit, a scientist with such training should be a member of the APOLLO crew to assure the most effective collection and on-surface analysis of observational and instrumental data.

CHAPTER III
MISSION PLANNING TECHNIQUES

A. ALTERNATE APPROACHES TO PLANNING

The most important task in the study was to establish priorities for observations and measurements to be made on the moon. These, in turn, were used to derive an optimum program for the astronaut's excursions as well as an optimum list of instruments for making recommended measurements. The utility of all feasible observations, for scientific and engineering purposes, must be balanced against the allowable time, weight and packing space, to arrive at a practical and scientific program of maximum value for study and exploration of the moon. Any list or set of observations that falls within the mission constraints (limits of volume, weight and time) may be called an allowable set. The objective of mission planning is to develop the best method of choosing the optimum allowable set out of the many combinations that might be conceived. Two approaches used might be arbitrarily classified as qualitative and quantitative in nature. The qualitative approach involved establishing optimum allowable sets by consensus of key members of the study groups. In the quantitative method, figures-of-merit were assigned to the various operations representing their utility in the different problem areas. Optimum allowable sets then were developed by processing with an automatic computer. The essential difference between the two methods was the manner of assigning merit. In the qualitative method, the operations were ranked by comparing them against each other; in the quantitative method, numbers denoting merit were given to the operations individually.

B. QUALITATIVE METHOD

The qualitative method of mission planning is fundamentally a trial-and-error process. A preliminary or first approximation to an allowable set is prepared by adding items, one by one, in descending order of importance until a limit in time, space or volume is reached. These limits permit allowable sets containing 25 items or less to be considered as a group. The preliminary set then is tested in detail by examining for inclusion of each of the items remaining. Inclusion of a new item entails exclusion of one or more of the original items, otherwise one or more of the constraints would be exceeded. The merit of the new item then is compared to the merit of all the items it might displace. Thus, each item, before being rejected, is tested against all the items chosen for final inclusion or against items of lower merit than those chosen. This results in the optimum allowable set, at least in the light of present knowledge of the moon.

At first, it would appear to be a formidable task to pick out approximately 25 items from the entire list of 107 selected measurements and then to compare each of the remaining ones explicitly with the original 25. The labor is greatly simplified because astronaut safety receives high priority;

practically all hazard observations automatically are included in all allowable sets. After that, priority is largely established by classes of measurements; it is obviously desirable to include major classes such as sampling, geology and geophysics in any allowable set. It is also desirable to choose observations whose results apply to the greatest number of problems and to favor those which can be done more effectively on a manned mission than on an unmanned mission. These requirements restrict the number of choices to an easily studied group. Mission schedules, in fact, were drawn up by the qualitative method and checked by the quantitative method. The only serious discrepancy is discussed in the following paragraphs.

C. QUANTITATIVE METHOD

In the quantitative or systems engineering method of mission planning, a data matrix is formed consisting of the values assigned to each measurement in the various problem areas and the weight, time, volume, and power required. The matrix comprises the input data to a computer program (see Part II, Chapter VI) which ranks the measurements individually by order of merit. This is done arithmetically, using a normalized figure-of-merit which relates the value of the measurement to the relative payload cost, i.e., fractional cost in terms of allotted weight, volume and time. The result is an explicit formulation of what was done implicitly in the qualitative method by comparing operations against each other.

The most important part of the computer processing is a second program to form a list of 100 allowable sets of highest value -- ranked in order of merit. Ranking in this case is based on the combined values assigned to the measurements in the allowable set, independent of their payload cost. The normalized figure-of-merit mentioned previously is only used in the ranking of individual measurements. Its purpose is to insure that high-value, low-cost (in terms of weight, power and volume) measurements are considered first in determining the 100 allowable sets of highest value and thus to reduce substantially the number of required computer operations. In this respect, the process resembles the qualitative method in that the computer assembles high-merit, low-cost measurements until one of the limits or constraints is exceeded, discards the last item and computes the total merit. The remainder of the list then is scanned repeatedly for possible substitutions, using a programmed sequence of dropping items or groups of items from the first allowable set and adding lower ranked items, in order, until one or more constraints are again exceeded. The total value (or merit) is computed for each allowable set and the set (or combination) and its value and payload cost stored in the computer memory. After the first 100 sets are assembled, each new allowable set is compared with the lowest ranking one in the memory and either replaces it or is rejected on the basis of value. In this way, a very large number of combinations are considered and the 100 highest in value are retained and printed out by the computer. For example, in the computer analysis of Flight I, Alternative I, a total of 668,303 combinations were considered, of which 3970 fall within the constraints.

By varying the weighting factors or priorities assigned to the different problem areas and by excluding certain classes of visual observations, a flexibility in mission planning can be achieved beyond the effective capacity of the qualitative method. Lists of allowable sets were computed both for weighting factors emphasizing hazards and engineering problem areas and weighting factors emphasizing scientific problem areas. Another list was computed with the visual observations omitted for comparison with a list in which they had been included. No significant differences in the results were noted. The program for the second mission was not planned quantitatively, but the instruments recommended were selected partly on the basis of their priority in the data matrix.

D. DISCUSSION OF RESULTS

Comparison of the results given by the computer with those of the qualitative method showed that the two approaches were in substantial agreement. The items at the head of the computer merit list and those most common in the 100 highest rated allowable sets were all in the qualitative allowable sets. There were, however, minor exceptions due to duplication or partial duplication or to being overlooked in the qualitative process. Chief among the latter was a set of maps. The original allowable sets were reviewed and revised in the light of the computer results, but no major changes were made.

One important difference in results was that the computer analysis did not assign comparably high priorities to all of the instruments in the Scientific Instrument Package. This occurred because such instruments required greater weights and volumes than other items of comparable merit. The decision to use the Scientific Instrument Package was not changed on the basis of computer analysis. This resulted from discussions indicating that the scientific value of telemetered data, acquired over periods much greater than the astronaut's time on the surface, is sufficient to warrant including the package.

PART II

CHAPTER I

GEOLOGY AND SELECTED GEOPHYSICAL PROCESSES

A. SUMMARY

Geological observations and measurements are the most valuable that will be made in initial stages of lunar exploration and are fundamental to the success of early APOLLO missions. Geology, literally earth science, is an extremely broad and diverse scientific discipline. It can be applied in lunar exploration, as on earth, to determine the past history and age, mode of origin, composition, occurrence of economic deposits, surface structure, nature and configuration of relief features, and to discover processes that modify and mold the surface. Indicative of the scope of geology is the definition presented by Sir Charles Lyell (1832), the Founder of Modern Geology, who observed: "Geology is the science which investigates the successive changes that have taken place in the organic and inorganic kingdoms of nature; it inquires into the causes of these changes and the influences which they have exerted in modifying the surface and external structure of our planet."

The geological section is divided into three major parts: field geology, geomorphology and compositional studies. Selected geophysical processes closely allied to geology also are included. These are exogenic radiation and flux measurements of micrometeoroids and primary and secondary lunar ejecta. Field geology involves the study of rocks, rock materials and their relation to one another; in geomorphology the formation, nature and development of surface features, the changes they undergo, and the processes involved are treated; compositional investigations consist of precise instrumental measurements that include age, radiological and radioactivity studies. By arranging the geological section in this manner, a logical progressive sequence is followed. The task sequence is to discover the nature and structure of the lunar surface, the arrangement of surface materials into relief features and the processes responsible for their development and finally, with more detailed and accurate measurements, to confirm and augment the observations of the field geologist.

As a group, the geological and selected geophysical measurements generally take precedence over the other scientific studies proposed for the APOLLO mission because they provide answers to such fundamental questions as:

- What terrain and environmental hazards exist on the moon?
- Of what does the moon consist?
- What is the character of the landscape?
- What radiological hazards and problems exist?
- Are useful mineral deposits available?
- Is natural shelter present?
- Can the lunar surface be traversed?
- How did the surface of the moon originate?
- What modifications has it undergone?
- What is the origin of the moon?

Astronaut safety is the primary concern of early APOLLO missions. Some serious hazards which may exist and for which geologic measurements and observations must be made are: (1) excessive radiation; (2) dormant life forms that could be injurious or fatal, especially if introduced onto earth; (3) damage by infall of meteoroids and micrometeoroids; (4) presence of electrostatically charged dust particles which may adhere to the astronaut and equipment or impair communications; (5) thick deposits of loose material in which the astronaut may be engulfed, mired or injured due to surface collapse; (6) reactive ultraclean surfaces resulting in vacuum welding of parts and generation of heat; (7) dangerous terrain configurations; and (8) abnormal reactions on contact with surface material, especially pyrophoric dust.

Geologic investigations contribute heavily to understanding of lunar trafficability. The extent, thickness, degree of cohesion, and structure of dust deposits and other surficial materials, as well as physical barriers presented by the lunar landscape and the occurrence of unstable and steep slopes, require measurements to assure eventual safe and efficient movement across the surface.

The ultimate success of lunar basing is dependent on comprehensive geologic studies. These will be valuable for identifying construction and support materials and predicting their probable occurrence. Field reconnaissance and geomorphic interpretation must be used to locate areas that will provide natural shelter. Delineation of rock types and structural relationships is imperative before selection of stable sites for permanent basing is made.

Rocks and surface features reflect the mode of origin and history of the lunar surface. Petrographic and other compositional studies of surface and near-surface rocks, observations on the configuration and origin of land forms and interpretation of structural features can be used to determine how the surface was formed and the sequence of events since its formation. For certain rocks, lunar history can be inferred from absolute ages derived by radioactive dating techniques.

Compositional studies of surface rocks and consideration of rock texture and fabric have direct application to determination of the origin of the moon. Each major hypothesis of lunar origin implies a particular set of rock compositions. Field observations and detailed compositional analyses of rocks should provide the requisite data for the first step in solving the question of moon origin. Absolute age of the moon as shown by radioactive decay rate measurement and comparison with the age of the earth will give insight to the relationship of the earth-moon system. Further understanding of the system can be attained by observations and measurements of the lunar surfaces, its relief features and the geomorphic forces that act upon it. Scientific studies on the moon constitute the first opportunity to study a celestial body other than the earth and one which is expected to have undergone fewer modifications. Such studies can lead to a better understanding of the earth and, with it, the earth-moon system.

Following are the principal geologic and associated selected geophysical measurements and observations proposed for the APOLLO study.

- Field Geology: thickness, texture, consistency and extent of surficial material and bedrock; attitude, contacts and structural relationships of rocks; exploration for deposits of useful materials

- Geomorphology: nature of surface features, their slope, relief, shape, orientation, and mode of origin; measurements and experiments to determine what forces act on the lunar surface and modify it, including particulate flux, micrometeoroid flux, thermal cycling, electrostatic transport, and the effects of gravity and outgassing

- Composition, Age, Radioactivity, and Exogenic Radiation: mineralogic composition, radioisotopic composition, elemental composition, stable isotopic composition, and special studies including age determination, exogenic radiation, chemical reactivity of the lunar surface, and experiments to determine the possible existence of dormant life forms

B. INTRODUCTION

Of the many scientific measurements, observations and experiments that will be performed on the moon, geologic applications will be among the most important. In the exploration of any unknown terrain, geology is always a fundamental consideration, especially in early stages. Lunar geologic data are not only critical for astronaut safety but provide answers to basic questions such as: is the lunar surface rough or smooth?--is it hard or soft?--is it steep or gentle? Geologic studies also will provide answers to more complex problems such as: what is the absolute age of the moon? has magmatic differentiation occured?--what is the sequence of land form evolution?--how did the moon originate?

1. Definition

Geology literally means "earth science" and was defined by Roberts (1839) to include all acquired or possible knowledge of natural phenomena on and within the globe. A science concerned with all phenomena on and within a planet is necessarily broad and diverse and consequently has been subdivided into 30 or more branches. It would be fruitless to apply all of the facets to geology in the initial stages of a lunar study; not only would it be tedious but many of the branches do not apply.

2. Organization of Geology and Selected Geophysical Processes Study Group

The application of geology to lunar investigations has been undertaken in three broad areas: (1) field geology, in which surface rocks and rock material and their relationship to one another are investigated; (2) geomorphology, where the origin and development and distribution of surface features are considered; and (3) compositional determinations, in which the composition of lunar material is the primary concern. This approach provides a thorough examination of the lunar surface, its relief features, its composition, and its rocks and their arrangement.

Mineral exploration is a portion of the field geology program. In making field studies, evidence will be noted of mineralization, metamorphosed and weathered zones, intrusive contacts, sublimate deposits, and related phenomena. The micrometeoroid and meteoroid environment is included in the geomorphological study because these phenomena are responsible for the formation of portions of the lunar landscape and may be active agents of erosion and transportation. Radioactivity is grouped with the compositional determinations rather than included in the geophysics chapter because it represents a special rock property and because radioactive materials are applicable to age dating from which important geologic inferences can be gained. Also presented in this chapter is exogenic radiation because of its natural alliance with lunar radioactivity and possible role in modifying the lunar surface. The organization of the geology and selected geophysical processes study group is shown in Figure I-1.

It should not be inferred that the field geology, geomorphology and compositional studies constitute the only branches of geology applied to the program. Several phases of geologic specialization are included in each of the three major groups. For example: the field geology program necessarily includes mineralogy, petrology, stratigraphy, volcanology, structural geology, physiography, and photogeology; geomorphic investigations will involve stratigraphy, physiography, volcanology, photogeology, and structural geology; and, to make encompassing compositional observations, geochemistry, crystallography, petrography, mineralogy, optical mineralogy, nuclear geology, and geochronology must be included.

3. Philosophy of Geologic Studies

A geologist, when initially confronted with the question of geologic studies on the moon, immediately thinks in terms of treating the moon as he would any unexplored terrestrial region and applying time-tested and venerated methods. As work has progressed on this program, it has become evident that

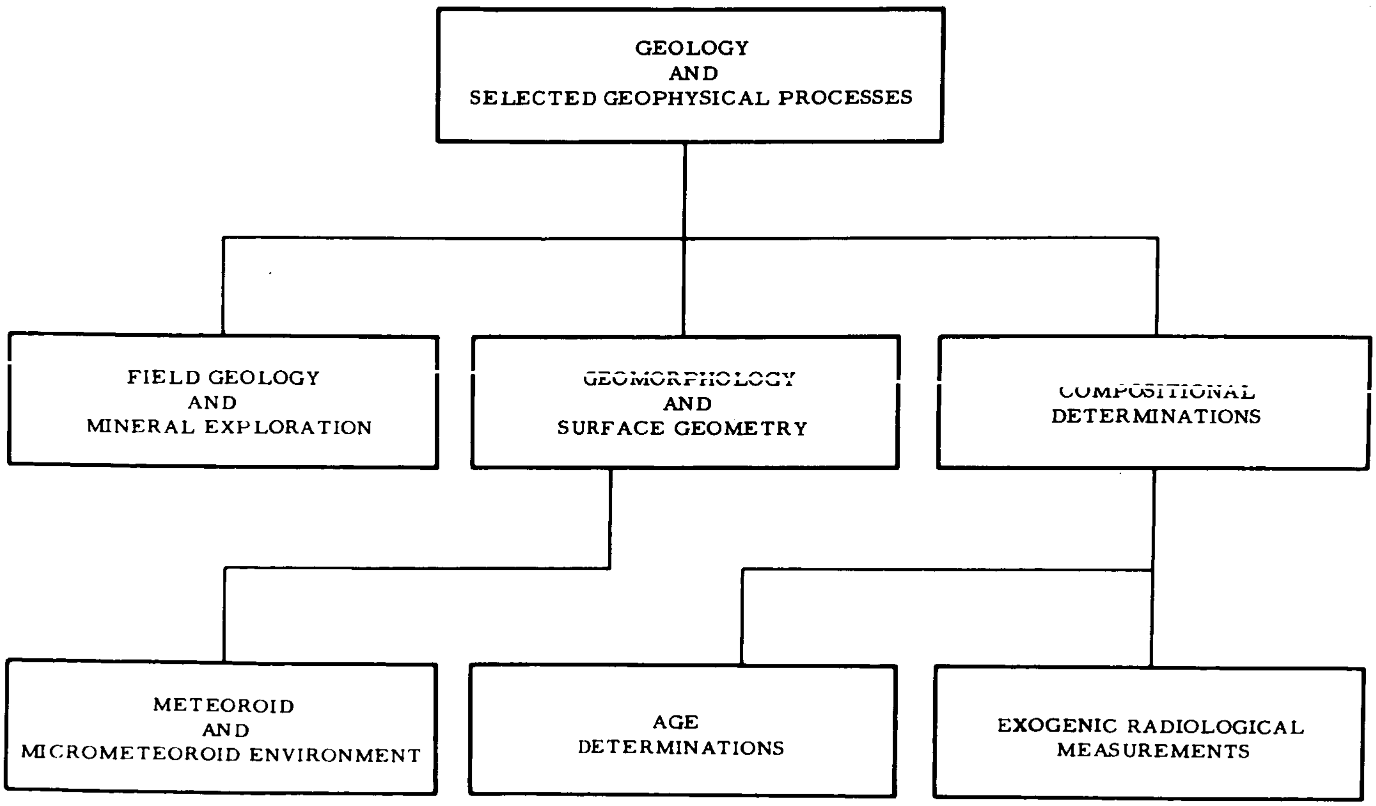

Figure I-1. Organization of Geology Study Group mission constraints, safety considerations, the nature of the lunar environment and practicality necessitate modified or different techniques. Certainly for early APOLLO missions, the scope of the investigations must be limited. What can be done, how it is done, the detail in which it is accomplished, and even why it is done are controlled by a multiplicity of factors entirely foreign to terrestrial studies. To illustrate, in planning lunar geological studies it must be remembered that:

- Safety precautions take precedence over scientific considerations.
- The astronaut will be encapsulated in a bulky space suit which will retard his movements and affect his agility.
- On early APOLLO missions, the astronaut will have a maximum of 2-1/2 hr on the surface at any one time. Much of this will be devoted to walking, emplacing and monitoring scientific instruments, and sampling.
- Limited available time will permit examination of only a small area, perhaps 1000 ft from the touchdown site.
- The restricted area of investigation probably will be structurally simple, topographically monotonous and perhaps monolithologic.
- Only small-scale topographic and photogeologic maps will be provided.
- A maximum of 80 lb of material can be returned to earth.
- The astronaut must remain at all times in view of the observer in the LEM.
- Space suit restrictions will not permit use of a traditional type of hand lens and will make it extremely difficult to make field notations on a map.
- Weight, volume and power limitations will dictate to a large degree what equipment can be taken to the moon.

- The lunar environment will be strange and alien. Lighting conditions, 1/6 gravity and surface conditions will restrict field geologic studies.
- Although the astronauts will be well trained, certain limitations in their training and experience must be considered.

Omission of some procedures customarily used on earth is not due to oversight, and modification of others has not been done in a perfunctory manner. Rather, the changes are a result of practical considerations and adaptations to restrictions of safety, weight, time, experience, and other mission constraints. In spite of the modified geologic approach presented, lunar geologic investigations must be undertaken using the classic geologic principles of uniformitarianism, superposition, faulting, intrusion, and unconformity. Similarly, scientific problems must be attacked using the concept of multiple working hypotheses.

C. FIELD GEOLOGY

1. Introduction

Field studies are the first requirement for obtaining geologic knowledge. In the initial stages of lunar exploration, field geological observations and measurements and related sampling will receive high priority and occupy a major portion of the astronaut's time.

a. Definition

Field geology (Lahee, 1941) is the study of rocks and rock material in their natural environment and natural relations to one another and includes description and exploration of surface features and underground structures. Field geology, as noted by Compton (1962), may be simple, involving visits to outcrops to describe them, or it may involve weeks or months of detailed mapping and careful integration of field and laboratory measurements. In either event, there is no substitute for observations made at rock outcrops.

b. Nature of Field Geology

A field geologist can make certain mechanical measurements, but fundamentally, his accomplishments are a result of observations and, for these, there is no substitute for training and experience. In this regard, the notation of Mackin (1963), in citing Gilluly, is especially pertinent: "Most exposures provide answers only to the questions that are put to them." Once observations are made, inferences are drawn by interpretation of the observed facts. The inexperienced observer may see little more than a mass of rocks at an outcrop, whereas an experienced investigator may note relationships that will aid in unravelling the history and structure of the neighboring region. It is necessary to do more than describe an exposure and record its attitude. Inferences may be drawn and hypotheses of origin and history made as well. As succinctly stated by Lahee (1941): "The ability to infer and infer correctly is the goal of training in field geology, for one's proficiency as a geologist is measured by one's skill in drawing safe and reasonable conclusions from observed phenomena."

c. Astronaut Capability

The success of the geological portions of the APOLLO program is a function of astronaut training and experience in geology. Although astronaut capability is a subject beyond the scope of this work, it is assumed that he will be familiar with the following subjects delineated by Kellogg (1963):

- Lunar Observations: the traditional ones now done from the earth (telescopic, radiometric, radar, emissivity, fluorescence, etc.) and the latest results of unmanned landings. Many of the moon's essential features presumably will have been made familiar by instrumented lunar probes.

- Field Geology: to gain insight into various types of formations (volcanic, impact), to develop the ability to perceive important features of those surroundings and to describe them clearly and objectively

- Laboratory Studies: laboratory studies in vacuum under various conditions of irradiation and proton bombardment

The astronaut also must have undertaken an extensive program of planning the proposed lunar field work. He should have a firm grasp of data included in geologic reports pertaining to the moon, as well as in technical papers and books dealing with fundamental concepts and methods pertinent to lunar exploration. He must be thoroughly familiar with existing astronomical and orbital photographs and lunar topographic and geologic maps. He should intensively study geologic maps and cross-sections prepared by the Astrogeology branch of the United States Geological Survey and be cognizant of the name, character and geologic age of each of the formations believed to be exposed in the touchdown area, those expected to underlie exposed formations, approximate thicknesses, structural relationships, general physiography, prominent land forms, the regional dip, and the anticipated lunar stratigraphic column.

d. Purpose and Scope

The scope of field work traditionally is threefold, i. e.: (1) to study and interpret rocks, topographic forms and structures; (2) to determine location of outcrops and points where geologic observations are made; and (3) to plot these points on a map or photograph. Mission constraints and lunar environment will alter the scope of field geology in the APOLLO program. In the first several missions, a maximum of 2-1/2 hr is available for all scientific observations and measurements. Although the proportion allotted to field geology may be great, time expended solely to geological observations will be insufficient to permit preparation of detailed maps. The astronaut is further limited by length of traverses. For example, on the first mission he probably will be able to go approximately 1000 ft from the landing site and return. Space suit restrictions will limit his physical activities. It will be extremely difficult to take legible notes, prepare usable sketches, make adequate entries on a base map, or even use an ordinary hand lens. He must use a communications link to a tape recorder to record his observations and use a hand camera to obtain photographs supplanting field sketches. His location and that of his observation and sampling points must be recorded on a map or photomosaic by the observer in the LEM.

Thus, the field geological studies on the lunar surface will be performed for the most part in a manner considerably different from customary terrestrial procedures. He will undertake reconnaissance rather than detailed geologic mapping. The astronaut-geologist will land on the moon in an area for which topographic and photogeologic maps have been prepared with considerably less detail than is usual in terrestrial operations. In view of mission constraints and the fairly gross nature of the available maps, the astronaut's task on early missions will be limited to geologic reconnaissance, observations made into a communications link to a tape recorder and collection of samples. Notation of position of observation and sampling will be made on a photogeologic map by the astronaut who remains in the space module. The field geologist will do rapid, sequential, decision-making work limited by the relatively brief excursion time largely to search (exploration) rather than research (experimentation).

Specific studies will depend upon determination of the most important areas of investigation, using the following approximate order of precedence:

- Contribution to the success of the present mission, with emphasis on recognizing and avoiding or overcoming hazards

- Contribution to the success of future lunar missions which will include: determination of trafficability conditions; establishment of lunar base; location of indigenous natural resources; checking accuracy of prepared geologic and topographic maps; and verification of topographic and geologic data to permit eventual point extrapolation to other areas of similarity on the lunar surface

- Contribution to the understanding of the origin, history and age of the moon and the earth-moon system

2. Field Geological Measurements and Observations

   a. Tasks and Procedures

The time required for geological work depends on the objectives, size of the area, roughness of the terrain, and complexity of the geology. If the lunar surface near the landing site proves complex on a small scale, more measurements and observations must be made and the sampling density will be much greater than if the local geology is simple and uniform. Among the more important scientific tasks are:

- Observation and assessment of natural phenomena including micro- and macro-structure and composition

- Collection of undisturbed and/or representative samples

- Emplacement of monitoring equipment left as an observatory

Observation of natural phenomena implies that the astronaut has the ability to give an unbiased or objective account of what he sees. However, it must be remembered as noted by Mackin (1941) that the "eye and brain unlike camera lens and sensitized plate, record only what they intelligently seek out." How much he observes and records can be increased by proper use of instruments selected and designed for specific tasks.

From his observation of terrain features prior to and after leaving the LEM, the explorer will select the traverse route that will allow safest travel yet take him by significant features where judicious sampling of rock types can be made. The traverse, of course, will begin and end at the LEM. Prior to leaving the LEM, the explorer should check radiation level and micrometeoroid flux, test the lunar surface for chemical reactivity and probe the surface with the multipurpose staff to insure that it will support his weight. Such probing may be necessary throughout much of his travel. It may be advantageous to calibrate the explorer's average pace in the 1/6 gravity environment against the spacecraft tracking device. If the tracker should fail during a mission, pacing would provide an alternate method of determining distances. Furthermore, in local areas where approximate distances are sufficient, it may be more efficient for the astronaut to pace distances between sample locations or geologic stations and relate them to the LEM observer than to obtain distances with the tracker.

Typical features to be noted and recorded for plotting on the field map in the lunar module are:

- Position and geometric orientation of contacts between rock units such as deposits of ejecta, breccia, talus, and dust, if preserved
- Domes, faults, fractures, joints, and other linear features plotted with appropriate geologic symbols and notation for upthrown side where faults are depicted
- Names or brief notes labeling important rocks and features including lithology and all small-scale structures helpful in interpreting the history of the rocks. Planar structures should be plotted as symbols showing strike and dip. Where apparent, compositional layering (banding) of igneous and metamorphic rocks and flow structures in igneous rocks, should be included.

The map will provide means to develop a continuous picture of geologic structures and, by communication with the LEM, permits checking of continuity of features (faults and contacts).

Verbal description, transcribed into a tape recorder, will include lithologic descriptions as noted:

- Name of unit and/or brief rock name
- Specific map locality or area to which description applies
- Thickness and overall structure or shape of unit in this area
- Main rock types and their disposition within the unit, if applicable
- Gross characteristics of area underlain by the unit: topographic expression; color and type of dust/rubble; nature of outcrops

- Characteristic structures of unit: range of thicknesses and average thickness of beds or other layered structures, if present; shapes of layers or structures; primary features within layers or other structures

- Description of rocks, with most abundant variety described first

  a) Color, fresh and weathered (radiation) and altered (impact, etc.) (Immediately after sampling, the freshly exposed surface should be described.)

  b) Degree of consolidation

  c) Grain sizes of rubble and other ejecta; crystal sizes (rock)

  d) Degree of equigranularity

  e) Mineral composition

  f) Shapes of grains and crystals

  g) Orientations or fabric of shaped grains, especially in relation to rock structures

  h) Nature and amount of matrix or groundmass, if any

  i) Nature and concentration of pores (porosity) and indications of permeability

  j) Constitution of grains (mineral, lithic, fossil, glass) and their approximate per cent by volume

  k) Abrasive hardness

- Nature and type of contacts: sharp or gradational, with description and dimensions of gradation; type of contact (conformable, fault, intrusive, or unconformable); evidence regarding unconformable relations

- Fossils (if present): distribution; special characteristics of the containing rock; position, size and condition of the fossil, and type, if recognizable

Observations of the astronaut are fundamental to a successful exploration program and, as noted by Newell (1963): "Every look he takes, every glance will be exploration." Observations and samplings are to be made with the primary objective of providing the maximum amount of information that will contribute to the success of the present and future missions. Sampling sites will be selected on the basis of visual survey and samples examined both in situ and in hand specimen, with the ultimate objective of possible selection for return to earth and detailed analysis.

b. Selected Measurements and Observations

Considered in the initial planning of the field geology phases of the APOLLO program were as many possibly relevant observations, measurements and experiments as possible. These were individually rated on a 1 to 10 basis according to their contribution to fundamental lunar problem areas (Appendix C). The numerical ratings are judgment values but provide a realistic estimate of the relative importance of the observations and measurements and, as summarized in Figure I-2 a concept of the relation of field geology to the individual problem areas. Field geological studies will contribute most heavily to the solution of problems and questions regarding the origin and history of the lunar surface, lunar basing and the origin and history of the earth-moon system. Applications to astronaut safety and lunar trafficability are more restricted.

Of the 83 measurements and observations initially considered, 30 were discarded because of duplication with other study groups or mission constraints. The remainder were re-examined relative to their contribution to the five fundamental problem areas, and 17 were retained for inclusion in the matrix decision system. They are shown in Appendix F and are discussed below. It must be reiterated that these were not selected in terms of conventional terrestrial field geology practices but rather on their contribution to the five problem areas, on the basis of mission constraints and in the light of the known lunar environment.

The field geological measurements, observations and experiments to be performed are determinations of:

- Rock composition
- Areal gradations
- Mineral identification
- Structures (kind, attitude and trend)
- Boundaries of surficial materials (horizontally and vertically)
- Texture of surficial material (consistency and composition)
- Localization of ore and its genesis
- Rock texture (grain size, shape, proportion of glass to crystal)
- Rock fabric (arrangement and distribution of grains)
- Bedrock exposures (attitude, extent, composition)
- Reflectance and emissivity of surface materials
- Kind and amount of ore minerals
- Stratigraphic sequence
- Formation contacts
- Attitude and extent of mineral deposits
- Rock color
- Abrasive hardness

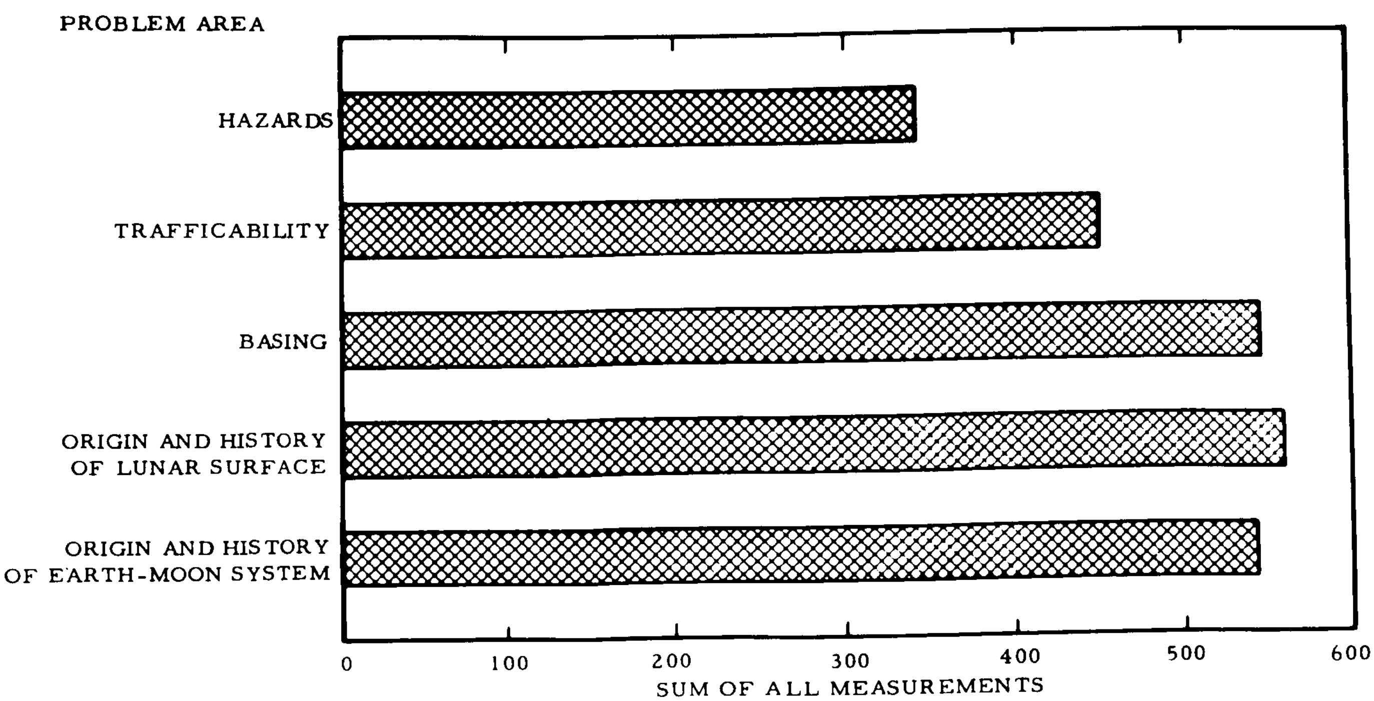

Figure I-2. Preliminary Estimate of Relative Contribution of Field Geology Measurements and Observations to Fundamental Problem Areas.

3. Importance of Measurements, Observations and Experiments Selected

Selection of the field geology measurements and observations was based on their contribution to the fundamental problem areas considered for lunar exploration. Reasons for selection are discussed by problem area.

a. Hazards

Thick, noncohesive dust deposits may be a serious hazard during surface geological operations. The astronaut may be engulfed or mired in dust, or a surface comprised of bonded dust particles may collapse under his weight. Thinly covered fissures and irregularities as well as unstable dust-covered slopes also constitute distinct hazards. The possibility of stirring up dense clouds of dust as the surface is traversed also must be considered. Electrically charged dust particles might accumulate on the spacesuit and on equipment and also might impair the operation of communications equipment. Measurements and observations of the consistency and composition of lunar dust, its areal extent, thickness, and rate of change of thickness will enable the explorer to know if dangers do indeed exist and, if they do, how they can be avoided or circumvented.

Rock texture and abrasive hardness measurements will indicate areas where excessive wear may occur and where sharp and abrasive rock edges may be abundant. Examination of structural features, especially those formed by faulting, will yield information which will reduce the possibility, even though remote, of hazards related to seismic ground motion and mass movements. Reflectivity and emissivity measurements have indirect application to astronaut safety. The measurements will provide data useful to understanding problems of lunar depth perception and the nature of shadowed zones.

b. Trafficability

Progress across the lunar surface can be impeded or stopped by thick deposits of loose material, especially uncohesive or weakly bonded deposits of dust. Measurements and observations to determine thickness, cohesion, consistency, and lateral extent of dust and similar surficial deposits, coupled with the measurements outlined in the chapter on soil mechanics are prerequisites before excursions, afoot or in vehicles, can be undertaken with any degree of confidence. Loose surface materials may collapse if weakly bonded, can cause loss of traction and eventual miring and can thinly cover fissures and crevices which will be subject to collapse when crossed.

Excessive wear at vehicle contacts with the surface, damage by sharp rock edges and, to some extent, excessive vibration can be avoided or predicted by careful measurements of abrasive hardness and by determining surface rock types and their mineral constituents. Geologic structures produced by faulting and folding may have produced topography difficult to traverse or that is a physical barrier to surface movement.

To predict which areas may be safe or unsafe for surface movements, areal gradations of bedrock, topography, dust deposits, and rubble must be known. Generally, careful visual observation will suffice for these determinations.

c. Basing

Field geological measurements are applicable to lunar basing in two broad areas: engineering-geological considerations and search for and development of lunar resources.

Site selection for lunar basing must be predicted on sound engineering practices. Of paramount concern are such factors as foundation stability, limiting unsupported slopes, grading and tunneling characteristics, energy requirements for excavation, load-settlement relationships, and cut-and-fill requirements. To obtain these data, measurements and observations must be made of the geologic structure, bedrock characteristics, areal gradations, rock type and hardness, rock texture and fabric, mineral composition, thickness, distribution and consistency of surficial deposits, formation contacts, and stratigraphic sequence. Stratigraphic and structural relationships also could be applied to locating areas where natural shelter may occur and areas that may be undesirable for basing because of unstable conditions or possible seismic activity.

Field investigations must be accomplished to ascertain the availability and extent of material that may be useful for lunar construction and future basing. Petrologic and mineralogic determinations and structural relationships are essential to discover suitable deposits of dimension stone, shielding material, fill, and possible supplies of aggregate.

Water on the moon may occur as ice in permanently shadowed zones, in volcanic sublimates or combined water in extrusives, as permafrost in subsurface material, in carbonaceous chondrites, or crystallized water in serpentine. Field reconnaissance and understanding of structural and stratigraphic relationships are required to identify possible zones of volcanic activity, ice deposits and permafrost occurrences. Rock and mineral identification and texture and fabric determinations are necessary in the search for sublimates and rocks containing combined water or crystallized water. Structural cross-sections prepared from field observations will provide an additional tool in the search for water sources.

d. Origin, History and Age of the Lunar Surface

Rocks, structures and topographic features of the lunar surface are evidence of its mode or origin and its past history. Geologic measurements to determine rock type and mineral content will indicate whether the surface is of volcanic origin, was formed by impact or by a combination of these and other processes. Inferences on the past history of the surface can be drawn from a thorough grasp of rock and mineral composition of bedrock and surficial materials and of rock texture and fabric. From rock composition, texture and fabric, evidence often can be gleaned regarding: magmatic differentiation and segregation; temperature, depth and pressure of formation; alteration since solidification; rate of cooling; mode of emplacement; assimilation effects; rates and direction of flow; composition of the magma; nature of the country rock; and the possibility of impact origin.

Structural and stratigraphic relationships repeatedly used on earth to determine historical sequences also can be applied to unravel past lunar history. These include: superposition of stratigraphic units; dislocation of formations; intrusive relationships; chilled zones; correlation techniques involving mineral constituents; and areal gradations and truncation of rock layers and structures by faulting. In some instances, color may be used to designate relative ages of surface flows or even of weathered surfaces. Composition of dust deposits and the manner in which they originated can be applied to understanding lunar history. These deposits may consist of volcanic fragments and may contain micrometeoroid fragments, phase-transformed minerals or shatter cones. Superposition of structural and topographic features and their dislocation may permit determination of their relative ages. This may be applied to faults, folds, impact and volcanic craters, fracture systems, and joint patterns.

Measurement of reflectance and emissivity properties of the lunar surface will contribute materially to knowledge of the history and origin of the moon's surface. From early APOLLO missions, detailed surface information will be obtained for only a small fraction of the surface. but remote sensing imagery from earth-based and lunar orbital missions will provide coverage of all of the earth-facing side of the moon. Areas with the same imagery characteristics for which ground data is available are considered analogous, and geologic and geomorphic relationships of the known areas can be extrapolated. Reliability of the extrapolation will be increased greatly if the reflectivity and emissivity properties of the landing sites are known, especially when augmented with data on surface configuration.

Reflectivity measurements also would permit assessment of existing geologic maps of the moon which constitute a considerable portion of geologic knowledge of its surface. Preparation of the maps is based on reflectance characteristics of large areas, and geologic units are delineated on variations in reflectance. Measurements on the lunar surface would enable an evaluation of the degree to which reflectance could be correlated with geologic data.

Determination of the absolute age of the lunar surface, using radioactive decay rates, is dependent on the occurrence of certain minerals and, of course, their recognition by the field astronaut. Sequences of magmatic activity can be discovered by sampling rock bodies. Exposure ages of meteoroids (Signer, 1963) may be determined by analysis of products of cosmic radiation and nuclear reactions.

e. Origin, History and Age of Earth-Moon System

Field geological measurements and observations can be applied to this fundamental problem in work concerning (1) origin of the moon as revealed by the composition and nature of its rocks, (2) absolute age determinations by means of decay rates of radioactive minerals and (3) interpretation of gross structural features to discover the major forces that have acted upon the lunar body in the past.

The principal hypotheses for lunar origin are cold meteoritic accretion with or without later radioactive reheating, cooling of a molten body, tidal separation from the earth, and gravitative capture of a large planetoid. The most revealing evidence of lunar origin is the material of which the moon is composed. Identification of rock types and mineral associations and a detailed examination of the texture, fabric and primary structures of rocks will be an indication of the manner in which the moon originated. The presence of basic and acidic igneous rocks and other evidence of magmatic differentiation would suggest a molten stage in lunar history. The absence of igneous rocks and dominance of aerolitic material would constitute strong evidence that the moon was formed by accretion or gravitative capture. If terrestrial sediments or mantle-like material are recognized, separation of the lunar body from the earth would be most likely.

Absolute age of the moon, contrasted to the recognized age of the earth, has direct application to understanding the earth-moon system. Radioactive mineral determinations and field reconnaissance are necessary to discover and select the applicable materials.

Gross structural patterns of the moon will indicate the forces that have acted and may now be acting on the lunar body. These forces may have been derived from internal stresses, impact or earth tides. Data accumulated from field geological studies of major fracture patterns and fold trends may eventually indicate the moon's past relationship to the earth and much of its history.

4. Nature of Property or Phenomenon Measured

All measurements and experiments deemed important for the field geology portions of APOLLO missions are passive, with the exception of abrasive hardness which is an active measurement involving partial destruction of the sample.

To determine the attitude and extent of mineral deposits, horizontal and vertical boundaries of surficial accumulations and nature and attitude of bedrock, both horizontal and vertical measurements must be undertaken.

Point measurements in the geological studies will provide valuable data, but multiple measurements should be made to determine all properties and phenomena selected. Multiple measurements are required because of areal variations and not because of time dependency.

The bulk of the measurements to be performed in the lunar geologic studies will be made in place, on samples extracted on the moon and again on samples returned to earth. This is true for the determination of: dust textures, consistency and composition; rock composition; mineral identification; ore deposit genesis; rock textures and fabric; nature of bedrock; kind and amount of ore minerals; reflectivity and emissivity; rock color; and abrasive hardness. Observations and tests will be at the outcrop, on samples removed from the outcrop and examined in hand specimen, and in the laboratory in a precise and detailed manner. Six of the measurements will be made only in place: boundaries of dust and other surficial material; structural trends, types and attitudes; areal gradations; stratigraphic sequence and formation (including intrusive) contacts.

5. Problems Associated With Field Geology Measurements and Experiments

a. Safety Considerations

The field geologist must be aware of lunar environmental conditions which may be hazardous and detract from his effectiveness. The intensity of sunlight to which the lunar explorer will be exposed is about twice as great as on earth because of lack of attenuation through an atmosphere. The resulting visual effects and potential physiological hazards may be controlled by filter techniques. Without such control, the sunlight may affect his observations. For example, in areas of massive, nonporous rocks, to the naked eye there may be little or no color difference in the terrestrial sense under the direct, high-intensity sunlight. Depending on reflectivity, illuminated areas may appear glaringly bright and shaded areas black. In the case of a porous surface exposure, light will be reflected only slightly. Consequently, visual contrast between neighboring surfaces may be very high. Based on terrestrial observations, dark maria areas have a visual albedo of about 0.05, whereas some of the brighter crater rims possess an albedo of about 0.40.

It is also possible that lighting variations may affect the astronaut's depth perception, but it is believed that such effects can be overcome quickly by relearning perceptual cues. Another consequence of the environment is that the astronaut may have locomotion problems due to modified functioning of his inner ear and the increased strength relative to his weight in the reduced gravitational field. He will need to exercise caution during his movements across the lunar surface, particularly during the initial period when he is adjusting to the new environment.

It is expected that portions of the lunar surface will be rough, with extensive areas littered by jumbled talus and ejecta. The astronaut must take care in crossing such areas to reduce the possibility of falls and brushing against sharp rock surfaces. A hand staff can be used as an aid in traversing these areas and as a probe in areas of dust or suspected surface weakness. If a penetrometer proving ring and gauge is attached, soil mechanics data can be obtained simultaneously.

In collecting and trimming rock samples, there is always a possibility of flying fragments of rock or metallic pieces of the pick. The astronaut should be aware of this hazard and adopt appropriate precautionary techniques.

b. Sampling

Sample collection is an integral part of any successful field program. Sampling, never an easy task, may be formidable on the moon, especially in view of the scant data available on lunar rocks and surface conditions, the limited time that can be used for sample collection, the diverse purposes for which the samples will be used, and the restriction of a return sample load of approximately 80 lb including exposed film.

Sampling of surficial material and surface and subsurface rocks cannot be performed in a haphazard or grab-bag manner. A carefully planned sampling program provided with alternative procedures must be devised and followed. In spite of limited knowledge of lunar geology, sampling procedure diversity can be illustrated with two extreme conditions that may be encountered. The lunar area of investigation may be geologically simple, i.e., consist of homogenous rocks and be uniform structurally. If these conditions prevail, a grid system of sampling based on statistical analysis might be the most effective and scientifically sound procedure. Stratified, systematic or stratified-systematic sampling methods, described by Krumbein (1953, 1954) could be used with the grid pattern. At the other extreme, the region to be sampled might consist of heterogeneous rocks and be complex structurally. A stratigraphic section might be exposed in a cliff, escarpment or crater wall and portions of the area be blanketed by dust of several types. Structurally, it could be transected by several faults and impacted by a meteoroid. A statistical sampling program would provide representative specimens, but the most valuable or critical evidence could be overlooked. It is apparent that the sampling program in this situation must rest with the astronaut. His training, power of observation and sound geologic judgment will be applied to determining where, how and what to sample.

Sampling programs for a wide variety of geologic configurations must be formulated. Consideration should be given the applicability of spot samples, serial sampling to test hypotheses, representative samples, sampling for bulk composition and distribution of composition, oriented samples, and subsurface samples. The purpose for which the samples will be used is a further consideration. Among uses of lunar material will be display, biological and chemical analysis, compositional studies, petrographic analysis, isotopic and age determinations, and engineering studies.

Additional difficulties in sampling can result from direct action of the individual doing the sampling. Attention must be given the possibility of sample contamination, and the astronaut must be aware of introducing bias in sample collection. He is also responsible for knowing and recording the precise location from where samples are taken.

The full payload of samples must be returned even if mishap has prevented acquisition of sufficient carefully selected specimens. On early APOLLO missions, any lunar sample is a good one and, if it becomes necessary to obtain the last few pounds of the payload indiscriminately, it should be done.

The foregoing discussion is indicative of a few of the problems associated with sampling. A separate, detailed study of lunar sampling methods, procedures and programs is recommended.

c. Field Geologic Maps and Photomosaics

Scale of geologic maps and photomosaics may seriously limit their application to field studies. It is planned to prepare them from Orbiter photographs, the scale of which is expected to be 1:20,000. Life support systems limit the astronaut to a maximum of a 2-1/2-hr operating range from the landing site. Considering uncertain footing, confusing lighting, high center of gravity, space suit problems, low lunar gravity and burden of equipment, the astronaut can progress approximately 1000 ft from the LEM in the time alotted for walking. At the aforementioned scale of 1:20,000, he can investigate about a 1-1/4-in. square area on the map. Furthermore, because of safety considerations and engineering constraints, the landing area will be relatively flat and featureless and, in all probability, geologically monotonous over an operating range of 1000 ft.

In spite of these difficulties, astronauts should be equipped with a photogeologic map of the area with a contour overlay. It can be enlarged and used for the purpose of orienting and locating features of interest. For plotting geologic data obtained in the field, photographs obtained during descent and printed and enlarged in the LEM are recommended. Descent photography is discussed in a following section of this chapter and in Chapter IV, Support Technologies.

6. Field Geological Equipment and Instruments

Equipment and instruments necessary for lunar field geology studies are not complex and, for the largest part, can be adapted with slight modification from existing equipment. Instruments required to perform the selected observations and measurements are:

- Hand camera with flash attachment
- Communications link to the LEM
- Photogeologic map
- Geologist's pick
- Multipurpose staff
- Sample bags
- Sampling tools
- Sample containers
- Gyrocompass
- Inclinometer
- Magnifying glass
- Sun compass
- Reflectance radiometer
- Magnet
- Light source
- Scale (for weighing samples)
- Hardness point

A geology kit, consisting of the items shown on Table I-1, will be carried on all flights. The remainder of the equipment required to perform field geological measurements either is (1) included in the sampling package (see p. IV-24 to 26), (2) incorporated in the spacesuit (communications link and magnifying glass), or (3) hand-held equipment (camera, staff, radiometer) which is listed individually on the mission schedules of Part I, Chapter II.

Detailed instrument evaluation sheets, including weight and volume values, are shown in Chapter V. A brief discussion of field geological equipment and instruments follows.

TABLE I-1

EQUIPMENT COMPRISING GEOLOGY KIT WITH WEIGHT AND VOLUME REQUIREMENTS

Instrument	Lbs	$In.^3$
Gyroscope with Inclinometer	3.0	22
Light Source (flashlight)	1.7	12
Scale (for weighing samples)	1.7	3
Sun Compass	0.3	3
Photogeologic Maps (3)	0.3	6
Total	7.0	46

a. Hand Camera With Flash Attachment

A camera capable of producing stereo photographs both in color and black and white should be provided for adequate performance of the field geological study. So photographs can be obtained in shadowed zones, the camera must be equipped with flash attachment. To record microstructures of rocks, dust and lunar soil, a special copy lens should be provided. A detailed discussion of the camera and film, including its application as a surveying instrument, is presented in the surveying, photography and mapping section of Chapter IV.

b. Communications Link

A tape recorder in the landing module will supplant the notebook and pencil conventionally used by the field geologist. The astronaut performing field studies can be provided with a transistorized transmitter and his observations permanently recorded. Tape recorders designed for space use by the Leach Corporation weigh as little as 7.5 lb, have been tested for operation for temperature ranges from -30°F to 165°F and are radiation-hardened for operation in the Van Allen belt. The equipment should be able to record ordinary conversation from 100 to 6500 cps. Leach Corporation has a contract to develop the tape transport of the APOLLO spacecraft, and it or a similar instrument would be applicable.

c. Photogeologic Mosaic With Contour Overlay

Despite scale difficulties and the impracticality of attempting to plot sample locations or attitude and structure symbols on a map, it is desirable for the astronaut to have a photogeologic map with a contour overlay of the region to be investigated. It can be prepared from photographs from unmanned missions and manned orbital flights. Even more desirable would be an enlarged photograph of the landing area and vicinity. Photographs could be taken with a descent camera from the hover altitude. The film would be developed, enlarged and printed prior to exit from the LEM. A 10-in. x 10-in. photograph could be prepared at either a scale of 1:1200 or 1:2400 and used by the astronaut to select traverse routes and features of interest and by the observer in the LEM to plot geologic data, sampling sites and traverse routes. Descent photography is discussed in more detail in the Geomorphology section of this chapter and in Chapter IV.

d. Multipurpose Staff

A multipurpose staff is a critical piece of equipment for the astronaut. It can be used as a walking staff to assist in traversing rough surfaces and steep slopes, as a rod to help maintain balance, as a pry bar, for a probe to be used in passing over surfaces of questionable bearing strength, and as a steady platform on which the hand camera can be placed for photography.

There should be consideration to converting it to a Jacob's staff by attaching an inclinometer and to adding a small magnetic appurtenance. If a proving ring and Ames dial were added, the staff could be used as a penetrometer to obtain soils engineering data. It also would be desirable to inscribe a scale on a portion of the rod and to paint it appropriately so it could be used as a ranging rod.

The multipurpose staff should be sturdy, of light and durable material and constructed to telescope into a short length to meet LEM payload constraints.

e. Geologist's Pick

A metallic pick of nonmagnetic material can be developed from existing models. Corners of the impact surface should be removed before use to reduce the possibility of flying metallic fragments. It is suggested that an easily read scale be inscribed on one edge of the handle.

Geologists habitually leave picks on outcrops, so it is recommended that a thong of appropriate length be attached to the pick so that once it is removed from the sampling package, it can be attached permanently to the space suit. It would be advantageous to have a spectroscopic record of the metal used in the pick (and of the metal in the multipurpose staff and sampling tools) so the signature of the metal could be used for comparison should sample contamination be suspected.

f. Sample Bags

Sample bags should be provided for return of specimens of rocks and surficial material. Modification of existing types with a special inner liner should be adequate. A system must be devised to avoid the common error of sampling and subsequently not knowing where the sample was obtained. One suggestion is to use bags color-keyed to designate the different excursions of a given flight inscribed with large, easily read consecutive numbers. Each sample location should be photographed, with the bag or bags included in the picture. Sample locations would be plotted (by the astronaut in the LEM) on the photo map of the landing site.

g. Sampling Tools

A combination sampling tool capable of cutting, sawing, pounding, and levering rock material and another to scoop up incoherent material must be developed. The knife blade can be used as a hardness point, and a small magnet might be embedded in the handle of one of the tools. Possible prototypes of both tools are discussed in the section on sampling techniques in Chapter IV.

h. Sample Containers

For delicate and extremely fragile samples, especially of bonded dust structures, special containers will be required. The pressure container discussed in the sampling section of Support Technologies, Chapter IV, is suggested for this purpose.

i. Gyrocompass

To measure directions, use of an instrument such as the Brunton compass cannot be relied upon because of meager knowledge concerning the magnetic field of the moon. A gyrocompass may be applicable for this purpose. Once a reference direction has been determined from inside the LEM by star sights or other techniques, the gyrocompass can be started and compared with the established reference direction. The gyro arrangement permits the rotor's spin to remain fixed in space (aligned to the reference direction) regardless of positioning of the base or outer gimbals. The spin axis provides a known reference direction and by using a sighting bearing circle, relative bearings of the strike of lunar formations, structures and trends can be obtained. This instrument must be developed for lunar use.

j. Inclinometer

An inclinometer can be attached either to the gyrocompass or to the multipurpose staff (converting it to a Jacob's staff). Incorporation of the inclinometer with the gyrocompass is probably the better choice inasmuch as bearings and angles then can be made with the same instrument. Angle of inclination of formations, topographic slopes, fault planes, and fold axes can be determined easily. The instrument is simple; lightweight, compact and easily read models can be adapted from on-shelf items.

k. Magnifying Glass

Magnifying devices are desirable to discern the representative qualities of rock, mineral and dust samples. Considering the encapsulated astronaut's limited dexterity and the 3-in. separation from eye to visor, any on-shelf hand lens would be inadequate. It may be advantageous to make a portion of the visor a magnifying lens or to provide an attachment that can be moved in front of the visor for magnifying purposes. This equipment must be developed and thoroughly field-tested.

l. Sun Compass

A simple compass rose with a central spike is a useful portion of the field geology package. It should have a circular scale concentric with the center pin so the latter's shadow length and apparent height can be gauged. Shades of gray and color hues can be arranged along the upper edges of the supporting base. The compass, when included in photographs of sample sites, rock exposures, joint patterns and similar features, will provide a means of determining the altitude of the sun when the picture was taken, orientation of the camera, position of the astronaut relative to the sun compass, scale, and a guide to the color of surface material. Bearings of a complex joint system or other intersecting linear features can be recorded with a single photograph if the sun compass is used. Only minor alteration of existing equipment is necessary to obtain a satisfactory instrument. A schematic drawing of the sun compass is shown on p. V-50.

m. Reflectance Radiometer

A hand-held reflectance radiometer which will measure reflected radiation in the ultraviolet, visible and infrared (to at least 14 microns) range is required for direct measurements of the reflectance properties of lunar surface material. The radiometer should be designed so that emissivity of these materials also can be determined. An instrument which can record from ultraviolet through infrared to 14 microns and which is acceptable for use on the moon must be developed.

n. Magnet

The astronaut should possess some means of testing rocks, powdered rocks and dust for their magnetic properties. The magnet could be included as a portion of the multipurpose staff or embedded in the handle of the geologist's knife. A wide variety of existing magnets can be used for this purpose.

o. Light Source

A light source such as a flashlight should be provided to assist observations in shadow areas. Without the illumination, it would be impossible to make in-place observations or perform meaningful measurements in the shadow cast by prominences of all sizes. Modification of existing equipment will be necessary and, of course, the lunar model must be light, durable and dependable.

p. Weighing Scale

Only 80 lb of material can be returned to earth. Weight estimates are not dependable, particularly in the unfamiliar lunar environment, so a spring scale should be included in the geological equipment package. The scale can be developed from on-shelf items but should be rugged, lightweight and need have only a 50-90 lb range calibrated to lunar gravity. The sample storage compartment in the LEM will have a liner which can be taken outside, loaded and weighed.

q. Hardness Point

The blade of the sampling knife included in the sampling package can be used to make rapid on-surface hardness determinations. In all probability, individual determinations with a blade of known hardness will be adequate. In this manner, it can be recorded if a rock or mineral grain is softer or harder than the metal of the blade or of equal hardness. However, if a wider range of hardness determinations is preferred, the sampling tools can be made of material of different hardness and determinations made accordingly.

7. Ranking of Field Geology Observations and Measurements

The following observations and measurements, listed in approximate order of importance, are recommended by the field geology study group:

- Rock composition: surface and subsurface
- Areal gradations: surficial material, bedrock, topography
- Mineral identification: surface and subsurface rocks
- Structures: folds, faults, linear trends, kind, attitude
- Boundaries of surficial material: horizontally and vertically
- Texture of surficial material: consistency and composition
- Localization of ore and its genesis
- Rock texture: grain size, shape, proportion of glass to crystal
- Rock fabric: arrangement and distribution of grains
- Bedrock exposures: attitude, extent, composition
- Reflectivity and emissivity of surface materials
- Kind and amount of ore minerals
- Stratigraphic sequence: correlation of rock horizons
- Formation contacts: position and orientation
- Attitude and extent of mineral deposits
- Abrasive hardness
- Rock color

Performance of these geologic measurements and interpretation of data derived from them will contribute heavily to astronaut safety, to insure success of future missions and to solution of the problem of lunar basing. Many of the measurements will lead not only to an understanding of the origin and history of the moon and its surface, but ultimately to a broader and more detailed conception of earth history and origin.

D. GEOMORPHOLOGY

1. Introduction

a. Definition

Fundamental to the problem of lunar exploration is the determination of characteristics of the lunar surface and its land forms. Geomorphology encompasses the description and understanding of relief features and is defined as that branch of geology dealing with the origin of landscapes, their form, nature, origin, and alterations. The science can be divided into descriptive geomorphology and genetic geomorphology or geomorphogeny. Descriptive geomorphology is concerned with the form and nature of surface features and the development of techniques to describe, classify, map, and compare features and areas. Genetic geomorphology treats the origin and development of surface features and the processes modifying these forms. In discussing terrestrial geomorphology, von Engeln (1942) observed that, inasmuch as the literal meaning of the word is a discourse about the form of the earth, it is necessary to consider the earth's configuration as a whole and the shape and disposition of its larger units in conjunction with the analyses of land forms. His attitude has been adopted in this study to render an inclusive treatment of lunar geomorphology.

A geomorphic investigation of the lunar landscape must be directed toward determining: (1) how the surface features were formed, (2) what forces modify them, (3) what their physical characteristics are, and (4) how they can be classified.

b. Land Form Classification

Land forms may be classified either on the basis of their mode of origin or by their configuration and composition. In the first instance, terrestrial relief features are divided into three broad classes, primarily on the basis of size. Secondary groupings are made within these classes to segregate land forms relative to their mode of origin. Surface features also may be classed with complete disregard of their genesis. The only concern is their size, shape and composition.

1) Genetic Classification

First-order land forms on earth, continents and ocean basins have lunar equivalents in terrae and maria. Second-order land forms are plains, plateaus, hills, and mountains, and the relief features of the moon readily fit into the same groupings. Third-order land forms are smaller features superimposed on second-order forms. On earth, they are exemplified by valleys, cliffs, basins, fault scarps, volcanic cones, alluvial fans, and sand dunes. In the lunar environment, such features as volcanic cones and craters, rilles, talus slopes, lava flows, walled plains, cliffs, and most impact craters comprise the third order. Within these major size groups, subdivisions are determined by the manner in which the land form originated. Genesis of relief features is a result either of endogenetic (internal) or exogenetic (external) forces. In the lunar environment, as on earth, endogenetic relief features result from: (1) compressive or tensional stresses within the crust forming folds, tilted surfaces or, in the event that rupture occurs, faulted structures; and (2) intrusive and extrusive volcanic activity. Volcanism may form vast array of possible features ranging from batholiths, laccoliths and lopoliths to lava flows, craters, domes, calderas, and explosion pits.

Principal exogenetic forces acting on the surface of the earth are running water, waves, wind, glaciers, and gravity. On the moon, it is probable that gravity, meteoroid and micrometeoroid impact, and particulate radiation are the main surface-molding agents.

The manner in which exogenetic and endogenetic forces act is used to classify land forms further. Some relief features are constructive (aggradational), having been formed by processes resulting in accumulation; others are destructional (degradational) and developed because of the removal of material. Grouping by this procedure has equal application to lunar features.

In a genetic classification, it has been shown that parallelism exists for lunar and terrestrial land forms, both on a broad-size classification and genetically insofar as endogenetic processes and constructional and destructional forms are concerned. The exogenetic processes are radically different. Many of the terrestrial surface molding forces do not act on the lunar surface, and the active processes play disproportionate roles to their terrestrial counterparts. Although largely subjective and qualitative, a genetic terrain classification is advantageous in that it has direct application to an understanding of the origin, history and age of the lunar surface.

2) Geometric Classification

A useful and objective method of classifying land forms is on the basis of size, shape and composition. The natural phenomenon responsible for the formation of a relief feature and whether it may be constructional or destructional is not considered. Rather, the material of which a land form is composed and the parameters which express its geometry are used for classification. A variety of parameters has been applied by different observers. Grabau (1958), for example, proposed using height, spacing, occupancy, hypsometric area, elongation, and parallelism. The parameters of Van Lopik and Kolb (1958) adequately describe a land form and are recommended for use in the APOLLO study. These are slope, relief, occurrence of steep slopes, and planar and cross-sectional shape.

A classification based on composition and terrain geometry has the following advantages: (1) when viewed in concert, a reasonably complete picture of a given terrain is provided; (2) a suitable method to test analagous terrains in either lunar or terrestrial environment is possible; and (3) the terrain parameters have meaningful application to problems of trafficability, mobility, hazards, and engineering requirements.

c. Modifying Processes

Another concern in geomorphology is the transient and continuous processes acting upon land forms and modifying their appearance. They have particular significance in understanding the possible cyclical development of relief features. If such cyclical development occurs, relative ages of segments of the lunar landscape can be ascertained. Furthermore, such processes may be directly applicable to the development of hazardous conditions, trafficability problems and basing considerations. The following are among the more likely processes resulting in the modification of existing land forms.

1) Meteoroid and Micrometeoroid Impact

In addition to forming fundamental topographic features, impacts subsequently alter existing forms by mechanical pulverization. Some of the fragments thrown out by the impact escape from the moon, some of the impacted surface might be vaporized or melted and other fragments are transported varying distances from the impact point. A large amount of debris will be produced, as each impact probably will eject debris many times the mass of the impacting body. Moreover, the larger ejecta fragments, as they strike the lunar surface, will produce secondary ejecta fragments.

2) Radiation

It has been suggested that X-ray and ultraviolet radiation could affect the internal structure of mineral crystals and also be responsible for the darkened surfaces of certain lunar areas. Therefore, radiation of this type is a slow, modifying activity that should be considered.

Exogenic particulate radiation may cause surface alterations by means of atomic sputtering. It is probable that some of the sputtered particles escape into space, and it has been estimated by Wehner, Kenknight and Rosenberg (1963) that sputtering caused by solar winds in the past 4.5 billion yr may have reduced the lunar surface by approximately 20 cm. Sputtering also may be effective in crusting or cementing loose particles of dust and other fine-grained surficial materials.

3) Gravity

Mass wasting is expected to be one of the most important gradational processes acting upon the lunar surface. As defined by Thornbury (1957), mass wasting involves the bulk transfer of masses of rock debris down slopes under the influence of gravity. The effects of gravity tend to reduce steep slopes, such as those formed by diastrophism, volcanism and impact. Lunar mass movements that may be active agents of planation and transportation are slow downslope creep of surficial material, slump, rock and debris slides, rock falls, and rock creep.

4) Volcanism

Volcanic activity, too, would modify existing relief features. Ejected blocks would be transported, and many might fragment on impact. Nearby areas would be blanketed with ejecta and depressions filled with ash and other ejecta.

5) Micrometeoroid Infall

Infall of fine micrometeoroid particles constitutes a depositional process of considerable interest--one which alters the appearance of the lunar landscape and would tend to stir and mix lunar surface material more or less continuously. Öpik (1962) estimated that a complete turnover of the upper 1-cm layer by the action of micrometeoroids would occur in approximately 10^4 yr.

6) Electrostatic Transport

In the ultrahigh vacuum of the lunar environment, charged particles may be transported by a series of bounds or hops. Gold (1955) first suggested that electrostatic effects may be adequate to give fine particles "fluidity". Singer and Walker (1962) are of the opinion that transportation of fine-grained material by electrostatic means is appreciable. Particle hops downslope would exceed those upslope, so this process would tend to assist the filling of topographic depressions.

7) Seismic Shock

Vibrations associated with moonquakes and to some degree with microseisms may be effective in reducing steep slopes to the angle of repose, thus acting as an agent for initiating rock transport.

8) Thermal Cycling

A temperature range in excess of 400°F occurs on the moon, setting up expansive and contractive forces in the exposed surfaces of rocks. These forces could cause spallation, granular disintegration and exfoliation. Temperature change as a method of mechanical weathering has been discounted by Blackwelder (1925, 1933). Griggs (1946), in experimental work on fatigue failure in rocks due to repeated temperature change, concluded the process was ineffective except in the presence of moisture. His experiments were conducted through a temperature variation of only 200°F and for a period equivalent to 244 yr of heating and cooling. More recent work in which a temperature change of over 400°F was used also showed that rock breakdown does not result from thermal stresses. In consideration of the vast periods of time in which thermal cycling has acted on lunar rocks, a condition not reproducible in the laboratory, this phenomenon should be considered a possible agent of disintegration.

9) Ice Thrust and Frost Heaving

Freezing of water to form ice involves a volume increase of approximately 10 per cent, and the expansive forces set up at -7.6°F may be as great as 30,000 psi. Water trickling into crevices and pore spaces in rocks and subsequent freezing can cause considerable mechanical weathering. If ice exists in shadowed zones or polar regions, rock fragments dislodged by ice thrust may be abundant.

If any moisture exists in the soil, lens-shaped masses of ice will form in time and the soil above will be heaved upward. Coarse rock debris tends to work its way to the surface, and a wide variety of solifluction features, including soil polygons, stone stripes and garlands, pingoes and thufur, may form.

d. Lunar Relief Features: Surveying and Mapping

1) General Statement

A few selected relief features are used as examples to illustrate some of the problems associated with the investigation of lunar land forms and to point out what might be observed. Several factors preclude application of time-honored terrestrial methods of field study. They include the limited distance the astronaut can traverse from the landing site, the requirement that he must remain within sight of the LEM, severe limitations of available maps, problems of astronaut agility and mobility, and operation in a strange and hostile environment.

2) Map Scales

It will be difficult for the astronaut to walk rapidly on the moon and, because he must exercise extreme caution at all times, it is unlikely that in the allotted time he will travel much more than 500-1000 ft from the LEM. On the 1:1,000,000 maps prepared by the Astrogeology Branch of the United States Geological Survey, this range is represented by 0.006-0.012 in. It is expected that 1:20,000 maps can be prepared from Orbiter photography. On a map of this scale, the maximum distance the astronaut will traverse is only 0.6 in. In all probability, the region of investigation will be geologically homogenous over this small area. Furthermore, since a touchdown area of minimum relief will be sought, there will be few, if any, significant topographic features. It is expected that resolution of Orbiter photography will permit recognition of features greater than 23 ft in diameter. To record details of features below resolution of Orbiter photography, the astronaut must utilize either a large scale map or verbal description keyed to ground and descent photography.

3) Descent Photography

A practical way to prepare a detailed map of the general vicinity of the landing area is to take pictures during descent, develop the film and print a photographic map after landing. Scale must be a compromise between what will be desirable for surface use and what can be printed conveniently in the LEM and (possibly) subsequently carried by the astronaut to locate features of special interest. A 10 x 10-in. map would be satisfactory for field use, and an enlarger to produce such prints would not be excessively bulky.

If a 120° lens is used in the enlarger, the print-to-negative distance necessary to enlarge a 2-1/2-in. negative to a 10-in. print is:

$$\frac{5 + \frac{2\text{-}1/2}{2}}{\tan 60^\circ} = 3.6 \text{ in.}$$

If the picture were taken with a 58.6° lens at approximately 890 ft, the picture would cover an area of 1000 x 1000 ft, a scale of 1 in. = 100 ft, or 1: 1200. To cover an area 2000 x 2000 ft from the hover altitude, a wide-angle lens (discussed in Chapter IV, Section C) would be required. The scale of the photo map would be 1:2400.

4) Investigation of Specific Topographic Features

In view of mission constraints, it is not simple to survey and map topographic features. It is advantageous to assess some of the inherent problems by examining procedures involving several lunar land forms.

Impact and splash craters probably will be more numerous than any other lunar relief features. Mapping of such craters should be undertaken because:

- Such craters constitute logical landmarks for survey tie points to establish the precise location of the LEM on Orbiter photography. Craters with diameters in excess of 23 ft will have sufficient tonal contrasts at low sun angles to define their shape for easy recognition.

- Impact penetration of the lunar surface may be sufficient to permit estimation of the depth of bedrock beneath surface dust and debris.

- Crater walls may expose a portion of the stratigraphic section and local structural features.

- The character of large craters may be interpreted from the relationship between the photographic and geologic character of smaller craters and their associated rays, halos and debris.

A major problem in investigating craters is that the astronaut may disappear from view of the observer in the LEM. Crater depth and diameter relationship, astronaut height and crater distance from the LEM must be understood to insure constant surveillance of the astronaut. Crater depth and diameter relationship has been studied by Baldwin (1963), Fielder (1961) and Fulmer and Roberts (1963). From their work, it may be assumed that apparent crater depth is about 22 per cent of apparent width and true depth is 17 per cent of apparent width. Fulmer and Roberts (1963) also observed that the depth of splash craters formed by lower velocity impacts is approximately 10 per cent of the diameter. Using these data, it is possible to compute for the craters of various depths the maximum distance at which the roving astronaut can be seen by the LEM astronaut. Computations are presented for two conditions: 1) if the astronaut is standing (Figure I-3); and 2) if he has fallen into a prone position within a crater (Figure I-4).

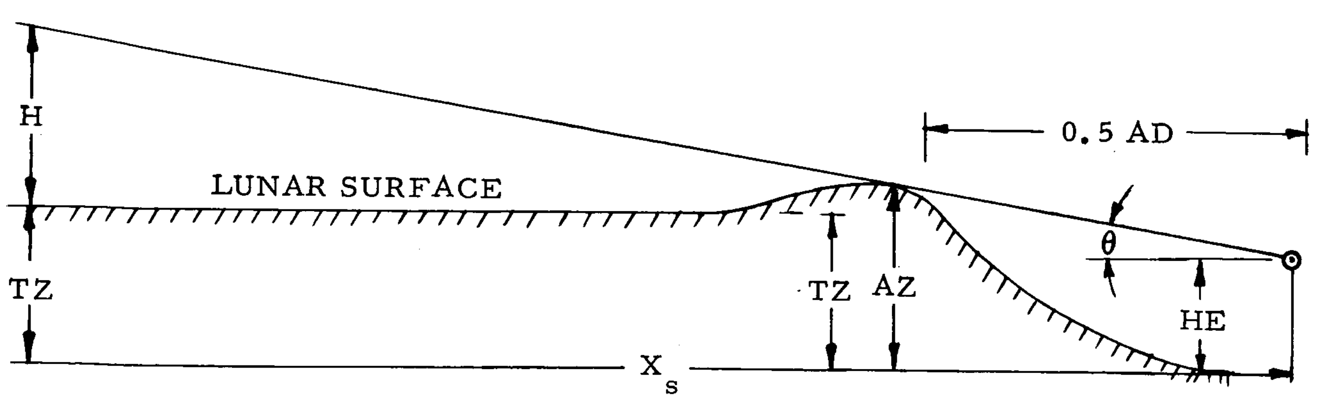

Figure I-3. Geometric Relationships for Computation of Maximum Distance At Which Standing Astronaut Can Be Seen From LEM

Symbols used to designate heights and distances on Figure I-3 are

θ = angle from horizontal to astronaut in the LEM
AD = apparent diameter
AZ = apparent depth = 0.22 AD
TZ = true depth = 0.17 AD
HE = height of astronaut's eye (5.75 ft)
H = height of eye of astronaut in the LEM = 16 ft (dependent on LEM landing gear penetration into surface material)
X_s = horizontal distance at which standing astronaut is visible to LEM astronaut

The value X_s is calculated as follows:

$$X_s = \frac{H + (TZ - HE)}{\text{Tan } \theta} = \frac{16 + (0.17AD - 5.75)}{\text{Tan } \theta} = \frac{0.5AD \; [16 + (0.17AD - 5.75)]}{(0.22AD - 5.75)}$$

Where the astronaut is prone (Figure I-4), a similar computation can be made. As illustrated, X_p is the horizontal distance a prone astonaut is visible and Tan θ = AZ/0.5AD = 0.22AD/0.5AD = 0.45. The value X_p = $\frac{H + TZ}{\text{Tan } \theta} = \frac{16 + 0.17\ AD}{0.45}$.

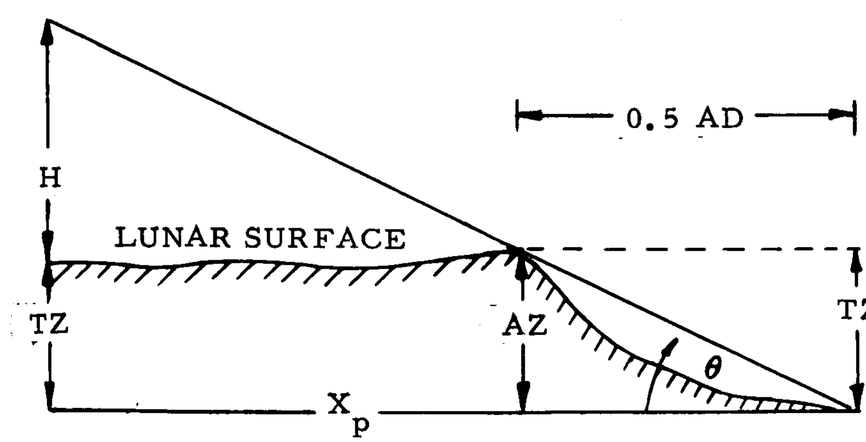

Figure I-4. Geometric Relationships for Computation of Maximum Distance At Which Prone Astronaut Can Be Seen From LEM

As shown in Table I-2, the apparent depth (AZ), true depth (TZ) and maximum distance at which the roving astronaut (standing and prone, X_s and X_p) can be seen by the LEM astronaut have been computed for various apparent crater diameters (AD). All measurements shown on Table I-2 are in feet.

TABLE I-2

MAXIMUM DISTANCE AT WHICH ASTRONAUT (STANDING OR PRONE IN CRATERS OF DIFFERENT DIAMETERS) IS VISIBLE TO OBSERVER IN THE LEM

AD	AZ (0.22AD)	TZ (0.17AD)	Maximum Distance Astronaut Visible: X_s (Astronaut Standing)	X_p (Astronaut Prone)
26.2	5.75	3.7	To Lunar Horizon	44
30	6.6	5.1	271	47
40	8.8	6.8	112	51
60	13.2	10.2	82	58
80	17.6	13.6	81	66
100	22.0	17.0	84	73
200	44.0	34.0	116	111
300	66.0	51.0	152	149

It is desirable to investigate the deepest crater in the study area to see if it extends into bedrock. A crater with a diameter of 300 ft would have a true depth of approximately 51 ft but it would be too hazardous to consider seriously a landing within the 152 ft required for astronaut observation. Probably, a crater, no more than 30 to 40 ft in diameter, can be investigated with the LEM close enough to permit surveillance of the roving astronaut and far enough away to obviate landing hazards.

If crater depth exceeds astronaut height, he may have to enter the crater from the side away from the LEM in order to remain visible, assuming the slope of the inner walls of that portion of the crater are not excessively steep. Once inside a crater, the roving astronaut could photograph the crater walls with the camera in a leveled position. Because of the slope of the lower segments of the crater wall and the camera's view angle, he may have to take one photograph standing and one from a kneeling position in order to cover the entire wall. The crater wall nearest the sun will be in a shadow and must be examined with a flashlight. A small electronic flash attachment will suffice for photography in shadowed areas if the film is reasonably fast. Very slow film would necessitate a large electronic flash in view of the poor light-reflecting character of most lunar rocks (see Chapter IV).

To survey an elevation into the crater, it may be necessary to photograph the LEM near the crater rim, place the multipurpose staff on the rim at this point, then enter the crater and photograph the staff.

Rilles, fissures and cracks also merit serious study. It is difficult to predict width-to-depth relationships of rilles and cracks, but Salisbury and Smalley (1963) are of the opinion that lunar crevasses would tend to widen as a result of impacts and slowly fill with dust and debris. They estimate that a crevasse initially 1-meter wide and 1-meter deep would be approximately 1.5 meters in width but only 20-cm deep after 3.5×10^5 yr. Baldwin (1963) summarized rille width-to-depth studies and on admittedly meager evidence suggested that depth may be expected to be 1/4 of the width.

The detectable resolution of a long, narrow feature begins at about 1/2 the optical resolution (refer to Chapter I, D-8) and, for Orbiter photographs, is about 4.6 ft. Applying the suggestion of Baldwin, a fissure or rille 4.6-ft wide would be only 1- or 2-ft deep but would be partially filled with loose dust and might have steep walls. An astronaut investigating rilles and cracks would be concerned with: (1) loose dust that might be present, (2) ability to stay within sight of the LEM and (3) how high a vertical wall could be traversed in a space suit. He can probe with the staff and will have had experience in climbing equivalent slopes in the terrestrial environment. He will remain in sight of the LEM if the walls do not exceed his eye level or about 5.75 ft.

Photographs of the walls of a rille, fissure or crack may reveal evidence of rock layering. Bearings should be taken along the strike, and depth, width and slope measurements made for trafficability studies. Photographs of the depth of footprints in the dust would be valuable for soils engineering studies.

Spread widely over the moon are numerous domes, many with central craters. It is expected that domes will have slopes not in excess of 2-3°, so it may be feasible for the LEM to land on or near one. Over a range of 1000 ft, a 2° or 3° slope would produce an elevation change of 35 to 54 ft--easily observable within the range of a 200-mm lens on a 35-mm camera.

Investigation of domes is scientifically advantageous. As outlined by Baldwin (1963), it is important to know if the dome has a central fissure, crater pit, pronounced joint system, or if there is evidence of flows. The alignment of an intricate network of joints could be recorded with a hand camera and a leveled compass rose with a central spike. The direction of shadow on the compass rose in the photograph would refer joint orientation to the bearing of the sun at the time the picture was taken.

Many younger craters on the moon exhibit a system of radiating rays nearly constant in width. The origin of these features is disputed; a review of ray genesis and its relationship to crater origin was presented by Shoemaker (1963). Sampling of the various ray and debris features radiating from craters would be important. It may be extremely difficult, however, to relate changes in tone and texture on photographs to what the astronaut can see on the ground. The possibility of a statistical sampling program at set bearings and distances around craters should be considered. It would be necessary to locate the center of the crater with respect to the LEM using the tracking transducer, then make sampling and photographic profiles on different bearings from the center of the crater. Sampling will show the relationship of particle size to observed photographic characteristics of rays which may be applied to ray interpretation of larger craters elsewhere on the moon.

e. Scope and Objectives of Geomorphic Study

From the standpoint of lunar exploration, form and nature of surface features will be of primary initial interest. Second, the forces modifying these forms should be investigated and finally, the origin and development of the features determined. This ranking is in accordance with the concept of first being concerned with factors affecting astronaut safety and the success of future missions and subsequently with scientific considerations. This does not mean that experiments and observations concerning all geomorphologic fields will not be made on a particular mission, but the relative importance of these fields in lunar exploration is quite clear.

Data concerning the form of lunar surface features, especially on the microrelief or microgeometry level, must be obtained to permit development of techniques for selecting areas suitable for future landings or basing and optimum routes for surface exploration.

When describing the surface geometry or form of any area, it is necessary to know the contour interval or terrain envelope being considered. Although objective and quantitative techniques can be developed to describe, classify and compare surface geometry at any scale or contour interval, lunar maps available at the time of the first landing probably will be inadequate from the standpoint of areal coverage, scale and contour interval to permit valid landing site selection. Consequently, it will be necessary to develop ways to predict the surface geometry at levels less than the contour interval of the best available maps. This requires knowledge of the micro and macrogeometry relations at several points on the lunar surface. Surface data and photography (at a variety of scales and resolution) must be obtained for several representative areas. Surface roughness or microgeometry data should be collected on early missions to permit development of techniques for: (1) extending or extrapolating such point information over areas where only small-scale photographic coverage is available and (2) describing and classifying specific areas as to their suitability for future landing sites. Probably, such data can be obtained best with stereo cameras or descent photography, but the astronaut should be trained to estimate slopes and distances accurately.

The processes modifying surface features are functions of time and, if mission constraints permit, will require leaving measuring devices on the surface, unless rapid erosion or deposition is underway that could be observed or recorded by cameras. Determinations concerning the origin and development of lunar surface features will require geologic and geophysical inputs and well-developed observational capabilities on the part of the astronaut.

The lunar surface presents a unique opportunity for geomorphological studies. Unlike the earth, it has not been modified by running water, covered and altered by oceans or changed by an atmosphere. Neither has any apparent obscuring effects of mountain building taken place with the magnitude or frequency present on earth. Thus, the moon's past history can be deciphered for a much longer interval, providing an opportunity to extend knowledge of solar system history much further back than has been possible heretofore.

From the introductory discussions, objectives of the geomorphic investigations are to

- Determine the mode of origin of lunar land forms
- Describe lunar land forms on the basis of composition and geometric characteristics
- Ascertain forces modifying existing land forms and attempt to determine the rate at which these processes occur
- Apply this knowledge to possible astronaut hazards, adequate lunar basing, selection of areas suitable for future landings, problems of traversing the surface afoot or by vehicle, and unraveling the history, origin and age of the surface
- Gain insight into the past history of the solar system

2. Geomorphic Measurements, Experiments and Observations

A total of 39 observations, measurements and experiments originally considered by the study group are listed in Appendix C. Of these, 25 are related to physical properties and 14 to natural phenomena. Most of these apply exclusively to geomorphic considerations but a few, such as petrology and mineralogic composition and texture, are more closely allied to field geology; strength and degree of cohesion are portions of soils mechanics; radioactivity is included in the compositional study; and seismicity is the primary concern of the geophysical study group. All are considered in this section as they are integral parts of landscape investigations.

The 39 properties and phenomena were evaluated from the standpoint of their contribution to the 5 fundamental lunar problem areas, and 22 were selected for further consideration. The major contributions of the geomorphic study (see Figure I-5) are to lunar basing, to an understanding of the origin and history of the lunar surface and to insuring astronaut safety. Physical properties to be determined, or a method by which they may be determined, in approximate order of their importance, are:

- Ground photography
- Topographic mapping
- Degree of cohesion
- Slope
- Relief
- Texture and mineralogic composition
- Occurrence of steep slopes
- Petrology of surface and near-surface rocks
- Degree of cementation
- Angle of repose
- Strength of surface rocks
- Orientation of topographic highs and lows

Natural phenomena related to land form development and modification for which measurements and observations should be made are:

- Areal gradations
- Micrometeoroid and meteoroid flux
- Electrostatic forces
- Radioactivity
- Erosion
- Thermal cycling
- Transportation mechanisms

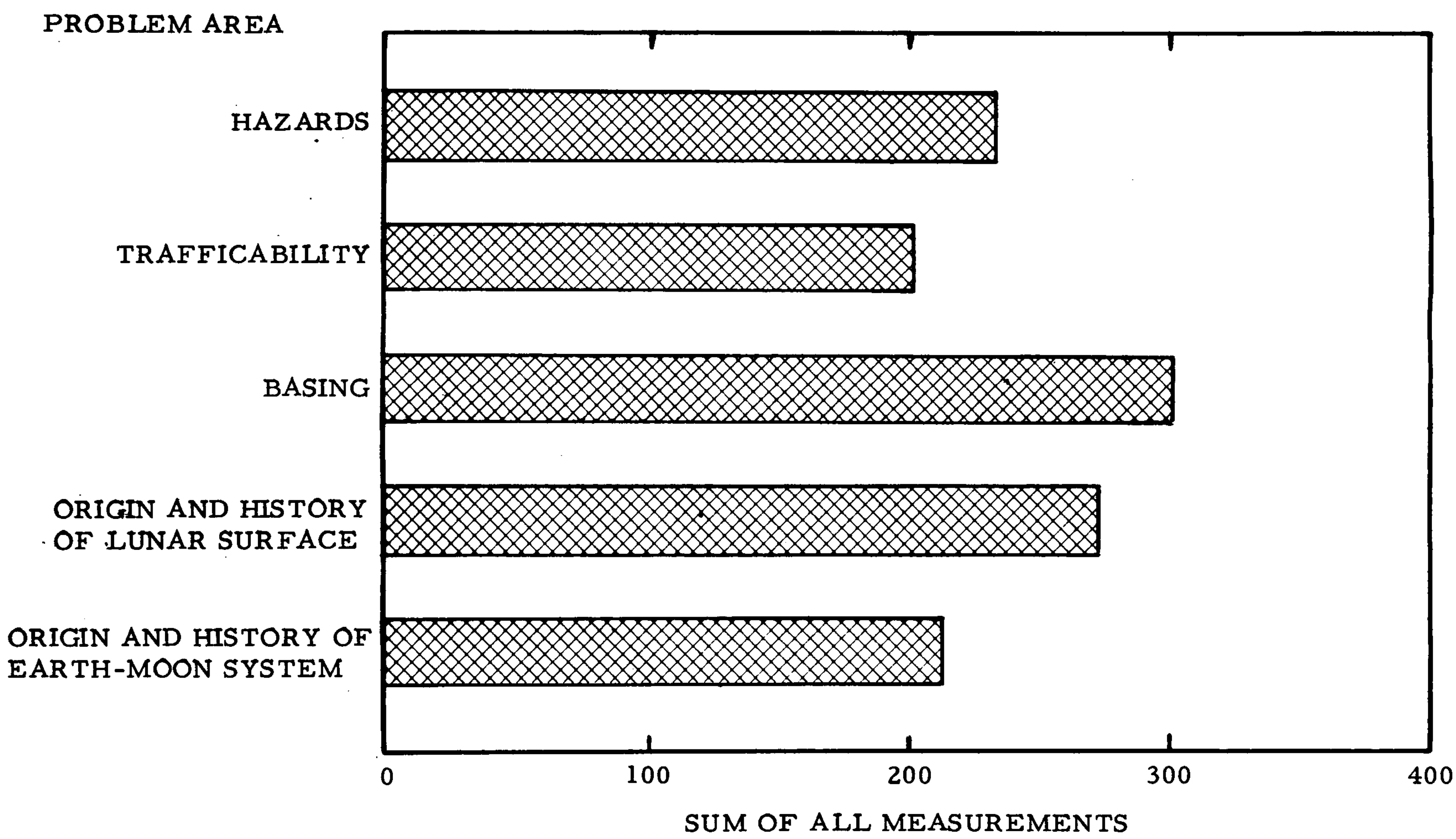

Figure I-5. Preliminary Estimate of Relative Importance of Geomorphologic Measurements and Observations to Fundamental Problem Areas

- Particulate radiation flux
- Vacuum outgassing
- Seismicity

3. Importance of Selected Geomorphic Measurements, Experiments and Observations

Contributions made to the fundamental lunar problem areas by the 12 geomorphic property measurements and 10 geomorphic phenomena observations are as follows:

a. Ground Photography

Ground photography is the most important geomorphology-related activity the astronaut can undertake. When coupled with adequate sampling of rocks and surficial materials, applications for ground photography are immense. It should be used first to verify the accuracy and detail of prepared topographic and geologic maps. Ground photographs also will provide a means for extrapolating point data to other areas of the lunar surface. Pictorial representation is a measure of ground truth and, by contrasting the appearance of the known area on orbital photographs to ground photographs, extrapolations to other similar areas can be undertaken. Ground photography, coupled with surface samples and the recorded visual observations of the astronaut, will furnish earth-based scientists with a reservoir from which extensive geologic, geomorphic and environmental studies can be made.

Ground photography applications to the five fundamental problem areas are:

1) Hazards

Photographs can be used to obtain some idea of surface inhomogeneity and the presence of sharp rock edges, abrasive surfaces, unstable slopes, and physical land obstacles to foot traverses and line-of-sight communications.

2) Trafficability

Visual observations complemented with ground photographs will provide data applicable to problems of both pedestrian and vehicular travel. Insight will be gained into vibration and loss of traction, occurrence of abrasive surfaces and sharp rock edges, the presence of physical land obstacles, and dust distribution.

3) Basing

The availability and character of natural shelter including lava caves and tubes, pressure ridges and caldera lip fractures, and undercut cliffs will be revealed by ground photography. Good ground photography will supply other basing data on surface geometry, nature and location of bedrock, presence of unstable slopes and fissures, horizontal distribution and continuity of ground materials, and recent faulting and volcanism. Direct evidence of possible lunar resources such as useful chemicals, mineralization, heat sources and water can be gained from lunar surface photographs.

4) Origin, History and Age of Lunar Surface

Photographic evidence of the distribution and nature of surface features, bedrock and surficial material is vital to understanding the origin and history of the lunar surface. Relative ages of some features can be ascertained and relationships to faulting, jointing and other structures observed. Variation in color and appearance of surface features may be evidence of the action of modifying processes and can be used to differentiate relative ages of formation. The effects of temperature change, sputtering and ice thrust can be recorded on photographs for subsequent interpretation. To a large degree, the controversy regarding volcanic or meteoroid origin of many of the surface features can be resolved from ground photographs.

5) Origin, History and Age of Earth-Moon System

Photographs of bedrock exposures should provide evidence of the occurrence of differentiation and indicate the possibility of a molten stage in the history of the moon. Evidences of seismic and volcanic activity will provide similar data.

b. Topographic Mapping

Mission constraints strongly influences the desirability of topographic mapping. Practical restrictions are discussed elsewhere in this section. Further, if accurate and detailed topographic maps can be prepared from the stereoscopic orbital and descent photography, need for topographic surveying will be largely obviated. Existing maps, however, should be verified by means of accurate mapping of even a limited area near the LEM touchdown site, preferably by stereoscopic ground photography. Additionally, data from topographic maps will be useful for extrapolation to other areas of similar appearance on the lunar surface as well as for providing some concept of the nature of surface roughness.

If adequate maps cannot be prepared from orbital, descent and ground photography, topographic surveying then becomes a major consideration.

c. Degree of Cohesion

The nature of lunar surficial material is controversial. An important aspect of the controversy is the degree of cohesion. This property received an extremely high rating because of its involvement in questions of basing, trafficability and possible hazards to the astronaut. The relationship of degree of cohesion of surface material to fundamental problems is as follows:

1) Hazards

If loose surface material is thick and poorly bonded or uncemented, there is danger of surface collapse and engulfment of the astronaut.

2) Trafficability

The degree of cohesion of surface material will affect strongly the possibility of traversing the surface and the rate at which progress can be made. If the material is thick and noncohesive, vehicles will mire due to loss of traction.

3) Basing

Cohesiveness of surficial material bears on many lunar basing considerations including unequal settlement, limiting unsupported slopes, nature of shielding material, energy requirements for excavation, and grading and fill requirements.

4) Origin, History and Age of Lunar Surface

In the event that particles are electrostatically bonded, vacuum welded or cemented by some other process, something of the history of the lunar surface can be inferred and a concept of several of the agents acting on the surface determined. Further, the degree to which the particles are bound together may permit postulation of the relative ages of portions of the surface.

d. Slope

Slope, the deviation of the surface from the horizontal, is a basic geomorphic characteristic. It is a necessary element of any geometric classification of land forms and is useful in determining genesis of relief features. Consideration of slope is also important to problems of trafficability and lunar basing and presents possible hazardous configurations.

1) Hazards

Areas of minimum slopes generally would be less dangerous than areas of steep slopes and would be premium areas for lunar operations. Rubble-covered slopes present dangers of falling, have an abundance of sharp rock edges and may be susceptible to mass movements. Steep slopes may present physical obstacles to foot traverse, and in steeply inclined areas, the astronaut is more apt to experience falls.

2) Trafficability

It may not be possible to traverse sloping surfaces, particularly if they are covered with loose rubble. Furthermore, steep slopes are subject to induced or natural sliding. Loss of traction and problems of vibration and wear are magnified in areas of moderate-to-steep slopes. Slope is a factor in the nature of surface roughness and in macrorelief relationships which strongly influence trafficability and mobility.

3) Basing

Basing doubtless will be in areas of minimum slope. Hence, slope distribution is a fundamental consideration. Limiting angles of unsupported slopes, areas of potential mass movement and surface roughness are related to the inclination of the surface.

4) Origin, History and Age of Lunar Surface

The occurrence of slopes can be used to infer the origin of relief features and the modifying forces acting upon them.

e. Relief

Observation and measurement of relief is fundamental to an understanding of topographic features and ultimately to their classification. Relief is defined as the maximum difference in elevation per unit area--an adequate definition in areas of moderate-to-high slope but not satisfactory for regions of low slope. A common division is to consider small-scale features as surface roughness or microrelief and the larger as macrorelief. The point at which macrorelief becomes microrelief is not well defined, and definitions of microrelief have set limits as high as 30 ft and as low as 1 in. In view of trafficability considerations, microrelief or surface roughness is defined in this report as those surface features exhibiting less than 3 ft of relief.

Lunar relief feature measurements and observations are critical for four of the five fundamental problem areas.

1) Hazards

Small-scale relief features will present a hazard to surface traverse, particularly by vehicles. Highly developed microrelief can cause excessive vibration, abrasion and immobility. Falling hazards and abrasion of shoes and space suit also may occur.

Large-scale relief features may impede the astronaut and subject him to possible falling and abrasion hazards as well.

2) Trafficability

Relief is a major consideration in lunar trafficability. Microrelief features can immobilize a vehicle and considerably impede foot travel. Excessive wear, vibration and equipment damage may occur in these areas. Macrorelief features often will dictate routes and, in many instances, block or severely impede progress on the lunar surface. Loss of visual and communications contact can occur easily in areas of high relief.

3) Basing

The sites selected will be in areas of low slopes and preferably of low relief, although steep cliffs adjoining a flat area might provide partial shelter.

4) Origin, History and Age of Lunar Surface

To determine the origin of the lunar surface and in part its history, it is a prerequisite that relief and variations in relief be known. Reduction of relief of land forms is evidence of modification. Areas of low relief must be examined thoroughly to understand their origin and to see if deposition has played a role in producing such areas.

f. Texture and Mineralogical Composition

The mineral content of surface rocks and the size and arrangement of mineral grains within these rocks can be applied to answering many geomorphic questions. Primary applications to the fundamental problem areas are to lunar basing and the origin and history of the lunar surface.

1) Basing

Texture and mineral composition of rocks largely will determine the strength of foundation material, energy requirements for excavation, foundation stability, and the problem of unequal settlement. Mineral composition is of utmost importance in the search for water resources, useful chemicals and, of course, possible mineralization of economic use.

2) Origin, History and Age of Lunar Surface

Absolute age of rocks of the lunar surface can be determined by means of radioactive minerals. Secondary minerals in rocks are evidence of weathering processes and coesite and stishovite of the meteoritic origin of associated land forms. Texture and mineral concentrations of other rocks will reveal whether deep-seated, shallow or extrusive volcanism has occurred. Mineral association also will provide strong evidence of the occurrence of magmatic differentiation. A historical sequence of events can be developed from accurate radioactive age dating.

3) Origin, History and Age of Earth-Moon System

Radioactive minerals can be utilized to determine the absolute age of the moon, to indicate a molten history of the moon and perhaps to provide data on possible reheating by means of radioactivity.

g. Occurrence of Steep Slopes

Slope occurrence gives some measure of dissection or the degree of irregularity of the surface. It is a parameter necessary for description and classification of landscape and has other applications as follows:

1) Hazards

Falling hazards, possibilities of induced or natural mass movement and physical land obstacles to communications and foot traverse are increased by the density of occurrence of steep slopes. These factors are also problems to trafficability.

2) Basing

Ideal basing areas probably will be of low slope occurrence. However, some steep slopes such as undercut cliffs and rilles may be useful as possible shelter sites.

3) Origin, History and Age of Lunar Surface

Steep slope occurrence provides information on the origin of surface features and their modification.

h. Petrology

Knowledge of rock type and distribution is fundamental to understanding the origin of the lunar surface and is also of utmost importance in lunar basing considerations.

1) Hazards

The type of rock present strongly influences the abundance of sharp rock edges, production of rubble and is a safety consideration with regard to flying fragments when samples are collected.

2) Trafficability

Rock type largely controls the abrasive quality of the surface, presence of sharp rock edges and the ease with which the surface can be traversed.

3) Basing

Perhaps the most important factor to be considered in lunar basing is the type of rock present. Petrology has direct bearing on such engineering requirements as foundation stability, energy for excavations, limiting unsupported slopes, availability of shielding material, and the amount of overburden that may have to be removed. It is also of paramount concern in the development of lunar resources such as shielding material, construction substances, mineralization, and useful chemicals and water-bearing sources such as obsidian, pitchstone and other igneous rocks.

4) Origin, History and Age of Lunar Surface

Lunar rocks will indicate whether the surface is of intrusive or extrusive origin, the degree to which modifying processes have been active, the role of meteoroid and micrometeoroid impact, whether magmatic differentiation has occurred, and zones of metamorphism and tectonic activity. Rock relationships also can be applied to developing a historical sequence of lunar events.

5) Origin, History and Age of Earth-Moon System

Rock type will control the occurrence of radioactive minerals for absolute dating and have a direct relationship to the origin of the lunar surface. From these, inferences regarding the earth-moon system can be drawn.

i. Degree of Cementation

In the terrestrial environment, cementation is one of the processes by which loose unconsolidated rock fragments are bound together to form certain rocks. If lunar rock fragments are cemented, then the nature of the cement and its origin must be determined to see how these particular rocks originate. Cementation increases the strength and cohesion of rock fragments and bears directly on lunar problems.

1) Hazards

If surface material is uncemented, noncohesive and thick, there is a danger of engulfment or surface collapse. Loose material stirred up by the astronaut also could impair visual and communications contact with the LEM.

2) Trafficability

Degree of cementation of surface debris and of rock surfaces partially will control the strength and bearing capacity of the material. Abrasion, excessive wear, miring, and immobility can result if surficial materials are uncemented.

3) Basing

Degree of cementation is a factor in the strength of materials. As such, it has application to lunar basing in terms of limiting unsupported slopes, unequal settlement and energy requirements for excavation. Furthermore, if soluble cements are the bonding agents, there is evidence that water, a vital lunar resource, was at one time present.

4) Origin, History and Age of Lunar Surface

If surficial material is cemented, the cementing agent is indicative of the origin of portions of the lunar landscape and of a portion of its history. Moreover, the degree of cementation may be used to determine relative ages of land forms, although this is not an infallible application. Soluble cements point toward the existence of moisture at some time in past history.

j. Angle of Repose

A necessary geomorphic measurement is to discover the natural angle loose material will assume under the influence of gravity. The angle of repose will determine slopes in loose material and where many mass movements may occur. Existing rubble slopes will affect vehicular travel and foot traverses and, in the case of lunar basing, will determine the limit of unsupported slopes. An understanding of the angle of repose of material of varying sizes will provide data on gravity's role in modifying the lunar surface.

k. Strength

Strength of rock materials is essential to trafficability and basing problems. Lack of surface strength may present a safety consideration.

1) Hazards

The strength of surface material must be determined early in the exploration program to evaluate the danger of collapse of bonded surfaces and the possibility of engulfment.

2) Trafficability

Collapse of surfaces, miring, abrasive surfaces, and loss of traction are trafficability hazards related to the inherent strength of the surface.

3) Basing

Foundation stability, settlement problems, energy requirements for excavation, and densification requirements are dependent for solution as on earth, on an understanding of the strength of rocks and surficial material.

l. Orientation of Topographic Highs and Lows

Strong parallelism in topographic highs will limit exploration at right angles to the topographic highs and tend to guide it along the parallel lows. Parallelism of topographic features can be used to determine major fracture patterns and thus reveal information on the history and origin of the lunar surface.

m. Areal Gradation

The simplicity or complexity of the lunar landscape is shown by the variety of surface features and rock types present and whether these variations are gradational delineations or are sharply outlined. An understanding of areal gradations will be valuable in checking the accuracy of prepared geologic and topographic maps and in extrapolating data from a restricted area to broader areas on the lunar surface. Specific applications are:

1) Hazards

Gradational changes will yield information that will enable the astronaut to avoid falling hazards due to lunar lighting variation, movement and communication difficulties due to physical land obstacles and possibly near-surface voids which might collapse under his weight. Areal distribution and gradation of fine-grained surficial deposits can be shown and their associated hazards avoided.

2) Trafficability

An insight into areal gradations will permit selection of traverses that will avoid highly abrasive surfaces, zones of sharp rock edges, areas of possible collapse, and zones where traction could be lost.

3) Basing

Sites for natural shelter can be deduced from consideration of areal gradations as well as engineering requirements for construction. Gradation phenomena can be applied to the search for possible chemicals, mineralization, water resources, and shielding material.

4) Origin, History and Age of Lunar Surface

Inferences on the origin of the lunar surface can be drawn from areal gradation of lunar land forms, surface rocks and debris. Age relationships then may be developed to assist in presenting a historical sequence of events in lunar history.

n. Micrometeoroid and Meteoroid Flux

These phenomena are practicularly of interest in the geomorphic investigation because they constitute the principal exogenetic force adding to and modifying the lunar surface. They are also important factors in lunar basing and in the determination of the origin, history and age of the surface. The nature and measurement of micrometeoroid and primary and secondary ejecta flux are discussed in detail in Section E of this chapter.

1) Hazards and Basing

Mechanical puncture of the space suit and damage to equipment by micrometeoroids and lunar ejecta resulting from impact are possible occurrences. It may be necessary to provide shielding to overcome damage to lunar bases, and the metal of meteoroids could be an important lunar resource.

2) Origin, History and Age of Lunar Surface

Many surface features of the lunar landscape may be formed by impact. If the flux is known, some concept of the relative age of features and the intervals required for their formation can be determined. Micrometeoroids and meteoroids also act as geomorphic agents of pulverization and of transport of fragments on the lunar surfaces and perhaps away from the lunar environment.

Absolute age determinations, applicable both to the age of the surface features and to an understanding of the earth-moon system, can be performed on meteoritic debris.

o. Electrostatic Forces

Electrostatic charges may bond loose fragments and also be a mechanism for transporting small rock particles. This phenomenon should be investigated as a portion of the geomorphic study.

1) Hazards

If dust particles are bonded electrostatically, several hazards to the astronauts will result. If the deposits are thick, there may be a danger of engulfment or miring on the surface. Dust may accumulate on the equipment and space suit and communications be impaired or negated.

2) Trafficability

Thick bonded dust deposits might make it possible to traverse certain portions of the lunar surface. Loss of traction, miring and excessive wear also could be caused by bonded dust deposits. Furthermore, electrostatically bonded particles may accumulate on the astronaut's boots to seriously impede his progress across the lunar surface.

3) Basing

Electrostatic charges may impede construction procedures and impair the operation of equipment. Thick deposits of electrostatically bonded material may have to be removed before construction is initiated, or shelters designed so that they will sink into the deposits.

4) Origin, History and Age of Lunar Surface

Electrostatic hopping of small rock particles may be an agent of transportation on the moon. The amount of movement, its effectiveness and the influence of slope and gravity on this process must be known in order to understand the phenomenon as a surface-modifying process.

p. Radioactivity

Radioactive emanations constitute a possible hazard to the astronaut, and the flux must be ascertained. Deposits of radioactive material are an important potential natural lunar resource. Most important, radioactive age dating will provide insight into the relative age of different portions of the lunar surface as well as the absolute age of the moon. In section F of this chapter, radioactivity and age determinations are considered in greater depth.

q. Erosion

Observations and measurements of erosive processes are most useful in understanding the origin of the lunar landscape but also are pertinent to lunar basing and potentially hazardous conditions.

1) Hazards and Trafficability

Particulate radiation, electrostatic hopping of charged particles, mass wasting, meteoroid and micrometeoroid impacts, and volcanic activity could be hazardous to the astronaut and endanger traverses across the surface. The occurrence and intensity of these processes should be determined.

2) Basing

The factors enumerated above are magnified in basing considerations due to the increased opportunity for damage because of the longer time of exposure of the base to the lunar environment. In addition, there could be possible disruption of surface material by frost heaving. Shielding requirements to overcome the effects of erosive phenomena must be examined.

3) Origin, History and Age of Lunar Surface

Obviously, to decipher the history and origin of the lunar surface, it is necessary to know the forces acting upon it. Until there is knowledge of what these are, how they act and their relative intensities, the lunar surface and its land forms cannot be thoroughly understood.

r. Thermal Cycling

Fluctuation of 400°F or more in lunar temperature has important ramifications. Thermal cycling may be an agent of rock breakdown due to the expansive and contractive forces it will cause in rocks. Space suits and scientific equipment must be designed to account for the extreme temperature range which also is of fundamental concern in design concepts for lunar bases. It is possible that, if cycling is an effective agent of rock disintegration, relative ages of rock exposures and land forms can be assigned on the basis of the degree to which they have been affected.

s. Transportation Mechanisms

Movement of rock particles across the lunar surface and downslope transport of rock debris are of scientific interest and have appre- cation to the fundamental problem areas as well. Modes of transportation and, if possible, rate and magnitude of movement of fragments by gravity, sintering, impact, electrostatic hopping, and explosive volcanism, should be determined. Particle movement might constitute a hazard by causing damage to equipment or space suit. It would be desirable to select areas for lunar bases where transport is negligible. The thickness, nature and mode of accumulation of transported debris in low-lying areas such as maria are of geomorphic interest. To understand the history and origin of the lunar surface, methods of transporting rock debris must be known.

t. Particulate Radiation Flux

Particulate radiation may be an important agent of erosion and transportation. It constitutes a distinct hazard to the astronaut. Not only may surface material be altered and eroded, but portions of sputtered surfaces may escape from the moon. Thus, the effects of particulate radiation and the rate of removal of rock material constitute another requirement to the understanding of lunar landscape origin. If rates of particulate erosion can be ascertained, relative ages of different surfaces that have been affected may be deduced. To determine shielding requirements for lunar basing, it is necessary to know the particulate flux. A detailed study of exogenic particulate radiation is presented in Section G of this chapter.

u. Vacuum Outgassing

Vacuum outgassing and/or volcanic emanations are geomorphic phenomena of concern. The astronaut should be alert for evidence of past outgassing and for zones of active vacuum and volcanic outgassing. The latter may be a possible hazard, either as a corrosive process or by causing thermal degradation of boots, LEM or equipment.

Outgassing may have produced usable sublimates, and volatiles from active zones could be valuable lunar resources. Evidence of volcanic activity indicates that molten material with entrained gases existed within the crust; hence, that the moon has had a molten or partially molten stage in its past history.

v. Seismicity

Moonquakes could be a minor hazard to the astronaut. More important, however, active seismic zones must not be neglected in basing considerations. Not only can moonquakes be a danger in themselves but they might trigger disastrous landslides. Seismicity determinations will contribute to knowledge of the origin of the lunar landscape and are the primary means of acquiring data on the interior of the lunar body. Some land forms will be of tectonic origin; others will be controlled by major fracture patterns. The nature of subsurface rock horizons and the internal constitution of the moon can be derived from the behavior of seismic waves generated by moonquakes.

4. Nature of Property or Phenomenon Measured.

The geomorphic properties and phenomena involve passive measurement in that they require no energy. All the measurements can be made in place, but those of the degree of cohesion, degree of cementation and strength can be undertaken most advantageously on extracted samples. Similarly, determinations of mineralogic content and texture and petrology generally can be made in place but, should unusual features and textural relations, unique mineral assemblages or exotic rock types occur, examination of extracted samples may be required. Many of the observations and measurements can be made on the moon, but selected samples should be returned to earth for detailed chemical analysis, petrographic and mineralogic examination and for performance of experiments to determine strength, degree of cohesion and degree of cementation.

None of the measurements or observations concerned with physical properties are a function of time as are those related to natural lunar phenomena. To obtain realistic data relative to phenomena acting on the lunar surface, it is necessary to perform experiments and measurements over a period of time--both single measurements at one location and multiple measurements at several sites. In the base of physical property determinations, both single and multiple observations should be accomplished for all properties with the exception of topographic mapping and three of the terrain parameters, i. e., relief, occurrence of steep slopes and orientation of topographic highs and lows.

Horizontal and vertical measurements should be undertaken for all of the property determinations except occurrence of steep slopes and orientation and planar shape of topographic highs and lows.

A more detailed listing showing the nature of the properties and phenomena considered in the geomorphic study is included in Appendix C.

5. Problems Associated With Geomorphic Measurements and Experiments

a. Safety Considerations

Acquiring geomorphic data on the lunar surface presents few hazards in that the required equipment is simple and has no energy requirements. Terrain and lunar lighting conditions constitute the principal sources of possible hazards. Unusual shadows and lighting, as compared to those on earth, will increase the possibilities of slips, falls and brushing against sharp rock surfaces. The astronaut must be especially cautious and avoid steep slopes, highly fissured and fractured terrain, unstable rubble slopes, and unusually rough surfaces. Care also should be taken to avoid flying rock fragments and/or metallic pieces when collecting rock samples with a geologist's pick.

b. Rate of Particle Transportation and Deposition

Measurements of the rate of particle transport on the lunar surface and the rate of accumulation of transported particles should be initiated as early as possible in the lunar exploration program. Although the astronaut may observe rock particles in the process of being transported and note deposits of eroded material, it would be advantageous to obtain quantitative data. A particle movement sampler (Figure IV-2, Section IV) has been proposed for lunar use, but it is difficult to devise adequate instruments before the nature of active transportation processes on the moon are known. Once visual observations on early APOLLO missions have divulged the character of transportation mechanisms and areas of particle accumulation, attention should be given to the design of applicable equipment that will provide reliable data on particle size and shape, mineralogical character and volume of transport.

6. Geomorphic Equipment and Instrumentation

a. Equipment List

Most of the equipment required for the geomorphic studies is simple and, in many instances, existing equipment or slightly modified models can be used. Detailed instrumentation evaluations including weight and volume values are shown in Appendix D. Geomorphic materials required are:

- Photogeologic mosaic with contour overlay
- Hand camera with flash attachment
- Communications link to tape recorder in the LEM
- Geologist's pick
- Gyrocompass with inclinometer attachment
- Multipurpose staff
- Magnifying glass
- Sample bags
- Sample containers
- Magnet
- Sun compass
- Light source
- Erosion trap

With the sole exception of the erosion trap, all of the equipment required for geomorphologic studies are discussed in the preceding section on field geology (p. I-22 to I-27).

b. Erosion Trap

A device to trap rock fragments in the process of being transported across the lunar surface is suggested in the sampling techniques portion of Chapter IV. An instrument must be developed which will provide reliable data on the volume of fine-grained sediment transported on the moon and from which information can be gained regarding mineralogic character and particle size and shape.

7. Ranking of Geomorphic Observations and Measurements

The geomorphology study group has concluded that the following measurements and observations will contribute most toward attainment of the APOLLO program objectives. In approximate order of their importance, they are:

- Ground photography
- Topographic mapping (using photogeologic methods)
- Degree of cohesion
- Slope

- Electrostatic forces as a bonding agent and transportation mechanism
- Relief: both surface roughness and topographic relief
- Areal gradations
- Texture and mineralogic composition
- Occurrence of steep slopes
- Petrology of surface and near-surface rocks
- Degree of cementation
- Angle of repose: from dust to coarse rubble
- Micrometeoroid and meteoroid flux
- Strength of surface and near-surface rocks
- Erosional processes acting on lunar surface
- Radioactivity
- Thermal cycling
- Transportation mechanisms
- Vacuum outgassing
- Seismicity
- Areal occupancy of topographic highs and lows

These geomorphic observations and measurements will lead to an understanding of lunar land forms and the nature of the lunar surface. Substantial contributions to astronaut safety, basing and the selection of future landing sites will also accrue. Data from the geomorphic studies will provide insight into the earth-moon system and permit a more searching investigation of the past history and origin of the solar system.

8. Extrapolation of Point Data

To obtain the maximum from early APOLLO missions, it is imperative to relate geological observations to orbital and descent photographs, infrared, radar, and other remote sensor data. Thus, a better understanding of large areas of the lunar surface from indirect evidence can be gained by means of direct observation of restricted areas. Extrapolation of point data can be applied to both geomorphic and field geologic observations, but for convenience is discussed only in the geomorphology section.

Tone, color, pattern, shape and size, both individually and in combination, are used to interpret terrestrial photography. It is important to determine how these properties can be applied to interpret photographs of the lunar surface and how the lunar environment may affect them. The primary purpose of all photographic or imagery interpretation should be to correlate image properties with surface geologic or physical properties of interest. Infrared and radar mapping systems convert changes in the intensity of reradiated or emitted energy in the infrared and radar parts of the electromagnetic spectrum to variations in the visible range and record these data on film. Hence, although the following discussion is concerned primarily with conventional photography, the analogous photographic properties of tone, texture, etc. must be used to interpret infrared and radar imagery. The significance of changes in image properties will differ among conventional, infrared and radar because they depend upon different physical phenomena. Consequently, interpretation of infrared and radar imagery can supplement conventional photography in lunar studies.

a. Tone

Tone is the measure of the amount of light reflected and recorded on film in terms of shades of gray. In the lunar environment, it will be determined by the albedo of lunar surfaces and by shade relief produced by surface irregularities. Definitive equations and curves for shade relief, photometric function and albedo have been outlined by Herriman, Washburn and Willingham (1963). Shade relief may be related to apparent luminances as follows:

$$B_1 / B_2 = 2^{S/2} \qquad (1)$$

where B_1 and B_2 are the apparent luminances of any two points or areas in camera view and S is the shade relief value.

Specifically, shade relief value indicates the number of shades of gray that can be detected realistically. It is an integral multiple of the minimum detectable tonal differences.

By substituting a shade relief value of 1 in Eq. (1), the luminance ratio between two points is

$$B_1 = 2^{1/2} B_2 \qquad (2)$$

Eq. (1) can also be in the form

$$S = 6.6 \log B_1 / B_2 \tag{3}$$

where $B_1 > B_2$.

In Eq. (3), there is similarity to photographic contrast as defined by Colwell (1960) who noted: "Contrast is the brightness ratio of light to dark in the target and is expressed as the common logarithm of this ratio. In actual targets and with recording film processed to a gamma of 1.4, it normally ranges from the recording threshold of about 0.025 to about 0.3 at high altitude and 1.0 at low altitude under favorable conditions."

An equation for contrast can be developed using the data of Colwell, namely

$$\text{Contrast} = \log B_1 / B_2 \tag{4}$$

For the threshold contrast of 0.025, $B_1 = 1.06\ B_2$, a 6 per cent contrast ratio, $\left(\frac{B_1 - B_2}{B_2}\right)$, is indicated as the minimum which can be recorded with a gamma of 1.4.

From Eq. (3) and (4), it is apparent that a contrast of 41 per cent is equivalent to a value of 1 shade relief, 100 per cent for a shade relief of 2. In addition, shade relief values are integral steps of brightness (luminance) ratios, i.e., gray tone shades whose amplitudes are in increments of the minimum recordable contrast. A safety factor of 6 is included to provide for different gamma processing and for degradation in the complete system.

Another approach to determine the minimum detectable difference of luminance was suggested by Rose (1948). For an ideal seeing device, a photosensitive surface detector, the following equation was derived:

$$\Delta B \geq r\, B^{1/2} \left(\Sigma H \frac{h^2}{d^2} D^2 t \right)^{-1/2} \tag{5}$$

where ΔB = the minimum detectable difference in luminance for adjacent small areas

r = threshold signal-to-noise ratio
B = scene brightness in foot-Lamberts
Σ = photosurface quantum efficiency
h^2 = element of area of brightness B in cm^2
$H = 1.3 \times 10^{16}$ photons/sec lumen
d = distance between scene and objective lens in cm
D = diameter of objective lens in cm
t = amassing or exposure time in sec

Contrast is conventionally defined by the equation

$$C = \Delta B/B \tag{6}$$

Substituting ΔB of Eq. (5) in Eq. (6), the threshold contrast below which a scene may not be detected because of insufficient tonal difference can be determined. Rose (1948) cited the threshold signal-to-noise ratio (r) to be greater than 3, but less than 7. Decker and Schneeberger (1947) stated that a signal-to-noise ratio of 7 is sufficient for a presentable picture, but 5 is considered a reasonable value.

The luminance of a given area at other than zero earth-moon-sun angle may be expressed as

$$B = 1/\pi \; E_s \, p \Phi \tag{7}$$

where E_s = solar constant
p = albedo
Φ = photometric function of the area viewed

Herriman, Washburn and Willingham (1963) noted that tonal changes induced by albedo differences decrease in earth-based lunar photography as the resolution of the observing system increases. In cases where this generality is valid and albedo differences are negligible over any given photograph, shade relief is redefined as

$$2^{S/2} = B_1 / B_2 = \frac{1/\pi \; E_s p \Phi_1}{1/\pi \; E_s p \Phi_2} = \Phi_1 / \Phi_2 \tag{8}$$

Since lines of equal brightness follow lunar meridians, the photometric function Φ to define the luminance meridian in question can be shown to be that of the phase angle g and some angle α. These angular relationships are summarized in the following simplified drawing, Figure I-6, where SQ is the incident ray, QE is the emitted or reflected ray to the observer, NQ is the normal to the surface, i is the angle of incidence, Σ is the angle of emittance, g is the phase angle, and α is the angle in the plane SQE between the intersection of the SQE plane with a plane normal to SQE containing both QN and the direction of emittance.

Pictures having a shade relief of 2 are considered marginal; those with a relief of 4, good. Theoretically, assuming slope values of 15°, shade relief values of 2 should occur at about 30° from the terminator, and values of 4 at 20 to 25° (Herriman, Washburn and Willingham, 1963). A practical check on the theoretical relationship was made by examining lunar photographs. Little detail was noted on photographs of areas beyond 30° from the equator, whereas areas closer than 20 to 25° showed good detail. This lends credence to the curves of the lunar scattering function of Hapke

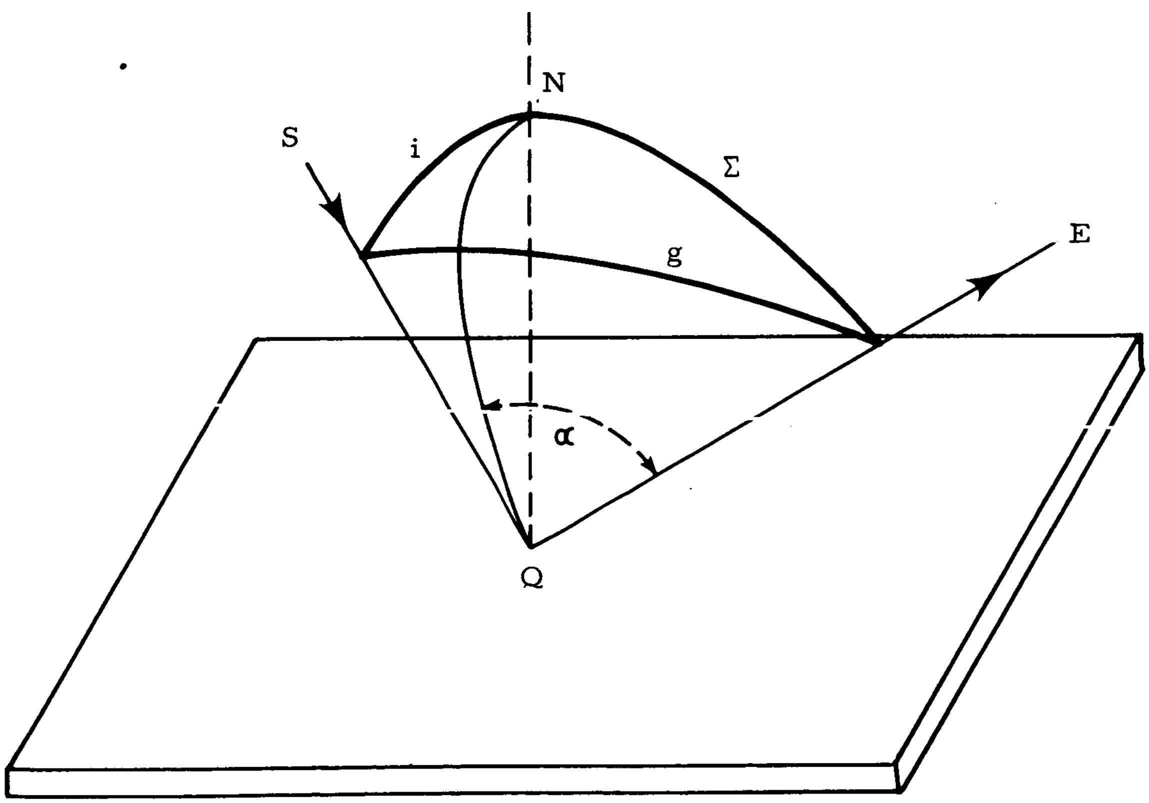

Figure I-6. Sketch Showing Relationship of Photometric Function and Luminance Meridian

(1962) and Halajian (1964). A representative curve, Figure I-7, has a narrow scattering peak indicating the strong dependence of the intensity of reflected light on the angle of the sun.

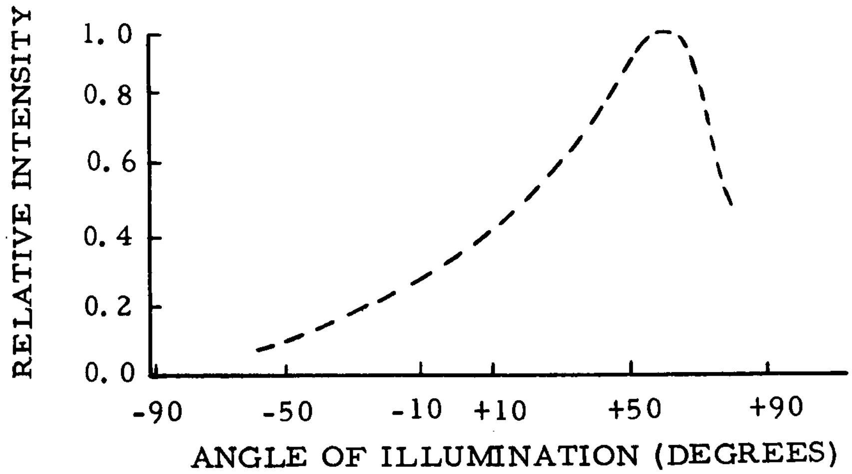

Figure I-7. Lunar Scattering Function for 60° Observation.

Surfaces of high albedo ($p \geq 0.3$) scatter light more or less diffusely, whereas those of low albedo ($p \leq 0.05$) have strong backscatter properties. Small differences in albedo have been measured, and mean values for various lunar features were determined by Sytinskaya (Kuiper and Middlehurst, 1961) as shown below.

FEATURE	ALBEDO
Dark plains (maria)	0.065
Brighter plains (paludes)	0.091
Mountain regions (terrae)	0.105
Crater floors	0.112
Bright rays	0.131

It is evident that most of the surface features of the moon have low albedo values. This contributes to the strong dependence on the sun-view angle in the reflection of sunlight.

b. Color

Color is one of the most important interpretive aids in terrestrial photographic interpretation, because the eye is capable of differentiating many more shades and hues of color than changes in shades of gray. Interpretation of lunar photographs includes large areas, and this relationship may not be as valid when photographs of a spot on the lunar surface are examined. In this regard, study of satellite photographs is suggested to determine how the color of earth changes when viewed from high altitude for calibration purposes.

A study of albedo and color variations on the moon was made by Sheranov (1958) who plotted color against brightness fields of lunar and terrestrial rocks. His curves, reproduced in Figure I-8, show that lunar rocks have low reflectivity and almost no color.

The earth's atmosphere is partially responsible for reduction of spectral contrast. Wavelengths near the blue end of the visible spectrum are attenuated until only about one half of the original intensity is available after transmission through one atmospheric thickness. However, about 90 per cent of the original intensity is transmitted through the red end of the spectrum. Hence, observation of the spectrum of the moon's reflected light through the atmosphere of the earth might be expected to show little contrast between colors near the blue end of the spectrum and attenuation in the red end. Photographs of the moon taken from earth-orbiting vehicles would largely overcome the reduction of color contrast, but some reduction would occur from the effects of dust particles scattered through interplanetary space.

Although color-brightness variations on the moon are apparently small compared to those on earth, changes in color and albedo have been observed in local areas. Green (1962) listed the occurrence of many observed color changes and Greenacre (1963) reported the observation of reddish orange spots on the lunar surface.

It is highly probable that photographs taken from an Orbiter within 22 miles of the moon or by an astronaut on the surface will not have as great a reduction in spectral contrast as those taken from the earth. Indeed, there may be much greater color ranges on the moon than is apparent now from earth observation.

c. Texture

Texture, a function of photographic scale and resolution, is the tonal aggregate of shapes and sizes. This produces a mottled appearance. The individual elements are too small to be measured or identified as discrete

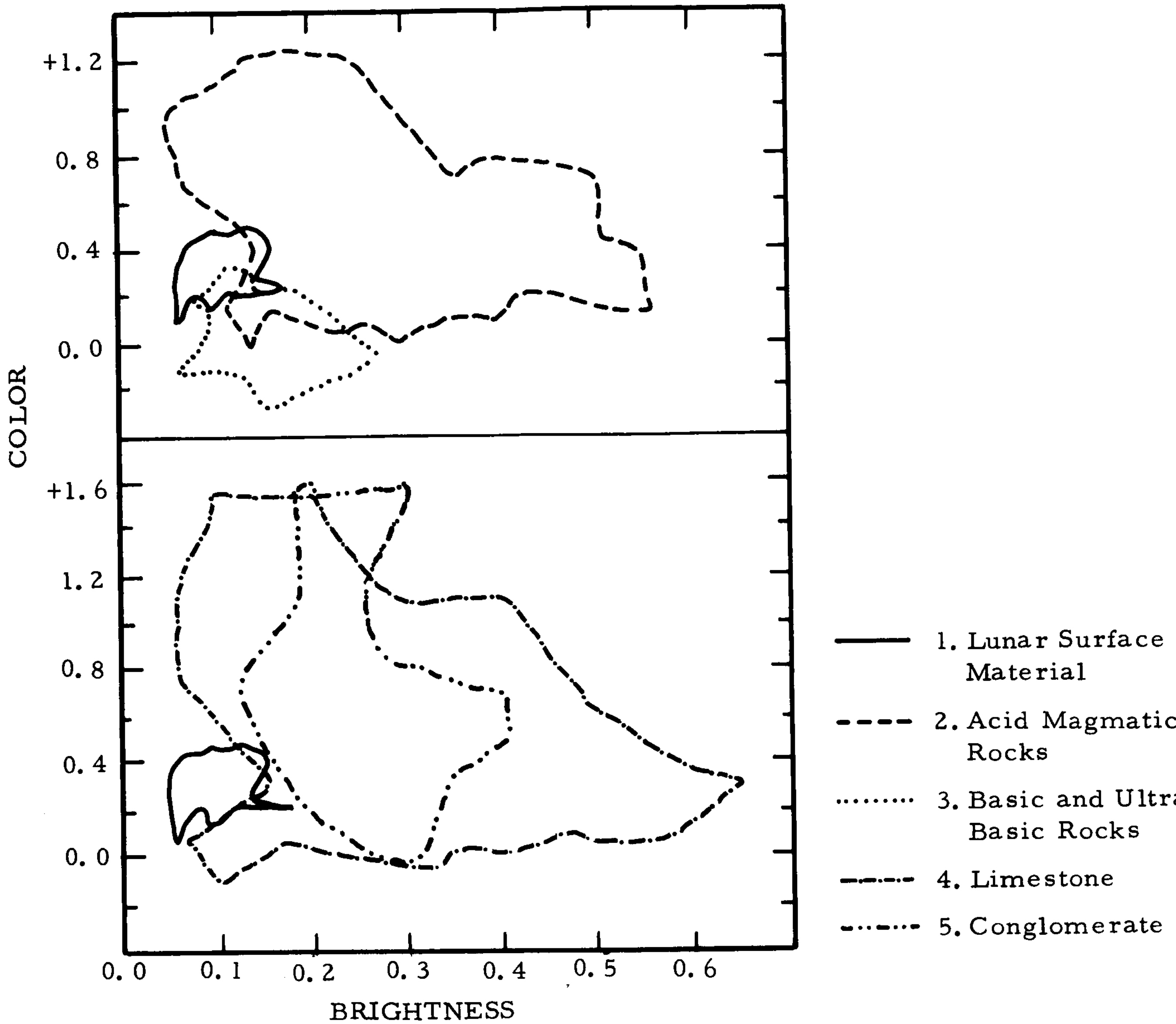

Figure I-8. Color and Brightness Fields of Lunar and Terrestrial Rocks. (After Sheranov, 1958)

shapes or sizes. In large-scale or high-resolution photographs, texture may be resolved into such specific features as hexagonal frost patterns, joint systems, faults, or individual masses of debris.

Texture on low-resolution lunar photography has been related to rough ejecta blankets, smooth maria areas and hummocky deposits around maria craters. The higher resolving power of orbital or descent photography may permit relating texture of observatory photography to pattern, shape and size of surface configurations producing the texture. Biba (1964) used an applicable technique to enhance the interpretation of sea-ice conditions. He related tone and texture on relatively low-resolution Tiros IV imagery to pattern, shape and size of ice features shown on high-resolution aerial photographs taken of identical areas on the same day as the Tiros imagery.

d. Pattern

Pattern is the ordered arrangement of geologic and topographic features in two and, in the case of stereographic photography, three dimensions. Patterns may be in the form of straight or curved alignments bounded by bedding planes, faults, joints, or lineations related to topography and/or structure. Rays, ridges, rilles, and valleys exhibit identifiable patterns on lunar photographs. Orbital or descent photography may permit identification of jointing, minor faults, rays around small craters, and perhaps smaller rilles.

e. Shape

Shape may be used on photographs to identify lunar land forms such as volcanic cones, craters, calderas, escarpments, and perhaps horst and graben structures. Shape is also a tool that has been used to study shadows of lunar prominences to determine slopes and to estimate relief.

f. Size

Size on lunar photographs is used to determine dimensions of topographic features, but it has only scalar significance. Numerous measurements of the size of lunar land forms have been made, but it is difficult to compare or interpret either their size or shape with possible lunar counterparts. In a recent study of crater-forming processes based only on size, it was found that lunar craters and domes are so different from terrestrial features of the same nature that they cannot be directly equated to one another.

g. Photographic Resolution

In addition to considering effects of photometric function, albedo and relief on tonal resolution, it is necessary to examine the resolving power of film and television camera systems. Camera resolution is critical for geological extrapolation because the particular pattern, diagnostic shape or special size relationships of areas investigated on the ground can be used as criteria to recognize the same features in unmapped areas. This can be done by measuring on the photograph such parameters as diameter, depth, roughness, length, width, strike, and dip. Resolution of the photographs will determine whether or not this can be achieved and, if it can, the accuracy with which it can be accomplished.

On photographic imagery, the minimum detectable detail is equivalent to one line or one space. This relationship can be expressed quantitatively by the ratio 1/2R. The value R is the resolving power of the photographic system in terms of the number of equal lines and space pairs per millimeter that can be recorded and distinguished on the photographic image (Air Force Cambridge Research Laboratories Report, 1963). However, there is a difference between detecting and identifying an object. Most observers agree that for an object to be recognized on a photograph, it must have an image about five times the detectable size or 5/2R mm.

The problem of television resolution was studied by Hall (1963). He concluded that with a minimum number of light flashes, it would require 14 television scan lines to recognize a test pattern consisting of 10 light and dark lines. Herriman, Washburn and Willingham (1963) determined that 2.8 scan lines are equivalent to one optical line pair. This agrees with Hall's results where 14/2.8 = 5 optical pairs, checking the 5/2R estimate.

A comparison of detectable resolution with the identifiable or geologic resolution r can be made using the data obtained by Lowman (1963). He used pictures taken on a Viking II flight with a K-25 camera having a 4.5-in. format and a 6-3/8-in. lens. The negatives were printed at 7X and the resolution estimated by identifying recognizable cultural features. From an altitude of 122 miles, the resolution was approximately 400 ft. The detectable resolution can be computed from the following expression:

$$G_{cl} = \frac{2\,A \tan(\theta/2)}{FS} = \frac{2 \times 635{,}000 \times 0.353}{40 \times 114} = 98'/\text{line} \tag{9}$$

where G_{cl} = ground coverage per camera-film resolution or detectable resolution

θ = camera view angle

A = altitude in feet

F = film format

S = camera-film system sensitivity

The geologic resolution, five times the detectable resolution, is 490 ft. This agrees closely with the resolution of 400 ft, based on recognition of cultural features, which Lowman obtained.

How do these resolutions compare with the specifications for Orbiter photography? Applying Kolcum's (1963) data, Orbiter photography resolution from pictures taken at an altitude of 22 miles is:

Operation Mode	TV Scan Line (Kolcum)	Resolution per Optical Line Pair (TV Scan x 2.8)	Resolution (ft) Detectable	Geologic
High Resolution, APOLLO Certification	3.3	9.2	46	23
Low Resolution, Surveyor Certification	16.5	23.0	23	115

A comparison of observatory photographic resolution with orbital photography also should be made. Estimates of the accuracy of terrestrial telescopes affected by the earth's atmosphere vary from about 0.25 sec (Kopal, 1962) to approximately 1.0 sec (Baldwin, 1963). This corresponds to distances of 1500 and 6000 ft, respectively, on the moon. The generally accepted value of resolution of lunar surface features is about 2500 ft. Using these data and estimates, the optical resolution required to detect a line pair and the geologic resolution are:

Technique	Resolution (ft) Optical	Detectable	Geologic
Unaided Photography	2500	1250	6250
Photography Aided by Visual Observations	660	330	1650
Theoretical Limit of 300-Ft. Length, 60-In. Aperture Telescope (Martz, 1963)	500	250	1250

High-speed film will decrease atmospheric blurring effects by freezing the image. This makes it possible to approach the theoretical limit of terrestrial telescopes (Martz, 1963), permitting slightly more detail to be recorded on film than is obtained now by photography aided by visual observations.

All investigators do not agree with some of the resolution data presented. This is understandable in that optical resolution depends upon the telescope, the weather during observations, observatory elevation and, to some degree, the observer's skill. Furthermore, confusion arises because, in some instances in published studies, there is not always a clear distinction between optical and detectable resolution. Regardless of these problems, the data presented are significant, even as first approximations. They show that the largest lunar features the astronaut will be able to investigate with his limited range of 1000 ft (on early APOLLO missions) probably will be smaller than what now can be discerned in photographs.

h. Concluding Statement

Geological studies of small lunar areas, coupled with orbital imagery interpretation, can be used to extrapolate data to many other portions of the moon's surface. This is the key to large-scale exploration and to a thorough understanding of the lunar surface.

E. MICROMETEOROID ENVIRONMENT AND LUNAR IMPACT EJECTA*

1. Micrometeoroid Flux

The flux of sporadic meteoroids approaching the moon should be essentially that approaching the earth; moreover, the lunar orbit is sufficiently close to the ecliptic that it is extremely unlikely that the meteor streams striking the moon are other than those which strike the earth. Thus, it would be expected that micrometeoroid flux at the lunar surface would differ from that in the vicinity of the earth only to a calculable extent dependent on the different gravitational environments of the earth and moon. There is little advantage in choosing the lunar surface for the study of micrometeoroid flux; it can be determined using probes or lunar orbiting vehicles. On early APOLLO missions, however, it is believed advantageous to ascertain micrometeoroid flux at a fixed spot on the lunar surface. This attitude is justified by the possibility, however remote, that micrometeoroids constitute a hazard during lunar exploration and by the role of micrometeoroids as a surface molding agent.

2. Primary and Secondary Lunar Impact Ejecta

Impact of various meteoroids with the lunar surface will result in ejection of lunar debris. A large portion will fall back on the surface and, upon impact, will throw up secondary ejecta fragments. Some of the impact debris leaves the surface of the moon with sufficient energy to escape into space. Because of this phenomenon, the impacts of meteoroids are thought to result in a net negative accretion rate. Other ejecta from the lunar surface will have energy sufficient to permit them to leave the vicinity of the moon and assume an orbit in the earth-moon system; such fragments would have velocities of about 11 km sec^{-1} in the vicinity of the earth and about 2 km sec^{-1} in the vicinity of the moon.

a. Particles in Orbit in Earth-Moon System

Particles of lunar origin launched into the earth-moon system might well result in an increased density of particles near the earth. This would cause satellite observations of micrometeoroid flux to appear anomalously high near the earth, inasmuch as some of the detection equipment could not distinguish between a particle traveling at 11 km sec^{-1} and a smaller particle of meteoroid origin at 30 km sec^{-1}.

Once launched into the earth-moon system, these particles of lunar ejecta will tend to orbit about the earth with their apogees extending to the region where lunar attraction can become predominant. In general,

*Contribution of A. D. Little, Inc.

however, the particle may orbit the earth many times before attaining its apogee at a time when the moon is favorably located to modify the orbit profoundly. The orbital characteristics of lunar ejecta entering the earth-moon system appear not to have been studied in any detail; clearly the ultimate fate of these particles is to impact on the moon or enter the earth's atmosphere. The relative probabilities of these two fates have not been calculated.

b. Particles in Ballistic Trajectory

Debris of lunar origin released in meteoroid impact on the lunar surface may have insufficient energy to escape from the moon; in this case, it will follow a ballistic trajectory on the moon and intercept the moon at a point determined by its launch conditions. Thus, on the moon, two types of particles not observable elsewhere should be measured: lunar debris returning from the earth-moon system at velocities of about 2 km sec^{-1}; and lunar debris in lunar ballistic trajectories at velocities below about 2 km sec^{-1}. The problem of distinguishing between micrometeoroids and debris of lunar origin renders relatively useless the more usual meteoroid detection equipment.

3. Number and Importance of Measurements

It is proposed to perform four measurements: determination of micrometeoroid flux, lunar ejecta flux, trajectories of lunar ejecta, and momentum of particles of lunar ejecta. It should be recognized that, although micrometeoroid flux measurement could be adequately undertaken other than on the moon, detection of ejecta flux, trajectory and momentum can only be made there.

These measurements are especially relevant to problems of lunar surface origin and history but also should be performed as a contribution to scientific knowledge. Micrometeoroid and lunar ejecta flux pose no problems to lunar trafficability but may constitute a minor hazard to the astronaut. The flux also should be determined so that, in the event it is of concern, design requirements can be specified for basing and equipment. Significant contributions toward understanding the origin and history of the lunar surface will be gained by measuring micrometeoroid and ejecta flux. Micrometeoroids are important agents of erosion and transportation. They form small craters and pulverize rocks upon impact, alter the appearance of the lunar surface and dislodge fragments of surface material. Some of the dislodged fragments have sufficient velocity to escape from the moon, and others are transported an appreciable distance from the point of impact.

4. Instrumentation State-Of-The Art

It will be necessary to develop an instrument to make micrometeoroid and ejecta flux measurements and a sensor for ejecta momentum determinations. Suggested devices are discussed in Chapter V, Section D, but the instruments are design concepts only.

a. Micrometeoroid and Lunar Ejecta Instrumentation

The type of instrumentation which could be used to make flux measurements and to determine the trajectories and velocities of particles of lunar ejecta relies on the following principle. The path of the particle is determined by locating two points on the trajectory where the particle passes through sensing screens; the velocity of the particle is determined by measuring the time of flight between these two points. Meteoroidal impact can be distinguished from ejecta impact in that it will result in only a single hole in the sensing screens; the vaporization of the debris from a meteoroidal impact will cause the momentum to be spread over so large an area that the second surface will not be penetrated.

Design concept of the instrument is such that it presents no known element of danger in either its emplacement or its use.

Another instrument, suggested by Jennison and McDonnell (1964) also might be considered. The device can be used to determine micrometeoroid flux and extended to measure the velocity and mass of the particles. Its operation is based on the principle that the potential attained by micrometeoroid particles in space is sufficient for detection of the particles by electronic sensors.

b. Momentum Sensor for Lunar Ejecta

The momentum of ejecta particles can be measured using a microphone or a fast-damped, microinch-displacement, solid-state sensor as a means of detecting the transferred impulse. A conceptual sketch of the instrument is presented in Chapter V, Section D.

5. Ranking of Measurements and Observations

A careful consideration of the relationship of the micrometeoroid and lunar ejecta measurements to lunar exploration and scientific value leads to the following rankings:

- Micrometeoroid flux
- Lunar ejecta flux
- Lunar ejecta momentum
- Lunar ejecta trajectory

Data obtained from these measurements will lead to a better understanding of the importance of micrometeoroids and ejecta particles as surface molding geologic agents and as possible hazards to the astronaut.

F. COMPOSITION, AGE AND RADIOACTIVITY

1. Introduction

a. Boundaries of the Study

This portion of the APOLLO project study is concerned with the instrumental measurement of:

- Mineral composition
- Chemical composition
- Radioisotopic composition
- Stable isotopic composition
- Density measurement
- Lunar atmospheric pressure measurement
- Detection of potentially dangerous dormant life forms
- Absolute age determination
- Radiological measurements (prepared by Arthur D. Little, Inc.)

These measurements have been considered for bulk samples, both in place on the moon and returned to earth, as well as for the separate mineral fractions of the samples. Both the surface materials and near-surface atmosphere are discussed.

The prime responsibility of this study group is in the areas of composition and age determination. Possible hazards due to space radiation and the detection of potentially dangerous dormant life forms such as viruses or bacteria are included because of the close disciplinary relationship.

In this report are discussed the following aspects of the compositional measurements which may be feasible on the moon:

- Lunar problems to be solved
- Measurements to solve them
- State-of-the-art instrumentation for the measurements
- Inherent problems in making the measurements

A brief general discussion of possible methods of age determination is included but, inasmuch as this complex measurement can be done effectively only on samples returned to earth, the necessary instrumentation is not covered in detail.

The section on radiological measurements was prepared by Arthur D. Little, Inc., under a subcontract and is included as a separate section as submitted by them except for minor editing changes.

It is believed to be of prime importance to obtain within mission constraints as many representative dust or rock samples as possible and return them to earth for measurement.

Restrictions of space travel, astronaut training, environmental operational problems, and short stay time permit only simplified and relatively approximate quantitative chemical analyses on the moon during early APOLLO missions. The major value will be obtained by using the much more complex and accurate earth-bound equipment on samples returned to earth. Measurements on the moon probably will be aimed at (1) insuring at least some results if samples cannot be returned to earth because of unforeseen difficulties, and (2) avoiding unnecessary duplication in selecting samples for return to earth.

Some measurements involving possible atmosphere may be practical only in the lunar environment.

The average lunar atmospheric pressure is thought to be less than that for the most perfect earth vacuum, and gaseous sampling probably will be possible only if volcanic gas vents are found. Otherwise, atmospheric determinations will be limited to gases contained in the lunar surface materials or adsorbed on them.

2. Compositional Measurements, Experiments and Observations

a. General Problem Areas

As a preliminary step in this study, a comprehensive list of possible compositional measurements was made. This included over 40 items rated individually on a 1 to 10 basis as to their relative estimated contribution of significant data in each of five general problem areas. These were:

- Hazards (to the astronaut)
- Trafficability (surface-bearing strength and mobility problems)

- Lunar basing (construction and supply)
- Origin and history of the lunar surface
- Origin and history of the earth-moon system

After filtering this list for practical and feasible methods, only 16 remained and these were rated on the 1-10 basis.

Figure I-9 is a summary taken from this final rating data. The estimated numerical relative contribution ratings for <u>all</u> the measurements were summed for each of the five general problem areas.

The greatest relative contribution of compositional studies is in the areas of lunar basing and origin, history and age. Contributions in the areas of trafficability and astronaut hazards are relatively minor. These are generally "by-products" rather than fundamental reasons for making the measurements except, of course, in the case of the detection of possible hazards due to dormant life.

A priority listing of the measurements as derived from the numerical estimated contributions is presented in Table I-3 . Only those believed capable of significant contributions in each problem area were included.

All of the numerical gradings are highly subjective but they do serve to give a feeling for the priority situation.

TABLE I-3

COMPOSITIONAL MEASUREMENTS BY PROBLEM AREA
IN ORDER OF ESTIMATED PRIORITY

Problem Area	Compositional Measurement	Problem Area Rating
Hazards	Sample Culture With pH Readout	9
	Sample Culture With Radioisotope Readout	9
	Gamma Ray Spectrometry	7
	Ion Gauge Pressure Measurement	6
Trafficability	Gamma Ray Backscattering	8
	X-Ray Diffraction	7
	Neutron Hole Logging	6

TABLE I-3 (CONTD)

Problem Area	Compositional Measurement	Problem Area Rating
Lunar Basing	Gas Chromatography	10
	Differential Thermal Analysis	9
	X-Ray Diffraction	9
	Mass Spectrometry	8
	Gamma Spectrometry	8
	X-Ray Fluorescence Spectrometry	8
	Neutron Activation Analyzer	8
	Infrared Spectrometry	8
	Ultraviolet - Visible Emission Spectrometry	8
	Neutron Hole Logging	8
	Ion Gauge Pressure Measurement	8
	Alpha Scattering Spectrometer	7
	Gamma Ray Backscattering	6
Origin, History, Age - Lunar Surface	X-Ray Diffraction	9
	Gamma Ray Spectrometry	9
	Mass Spectrometry	9
	Neutron Activation Analysis	8
	X-Ray Fluorescence Spectrometry	8
	Alpha Ray Spectrometry	8
	Gas Chromatography	7
	Ultraviolet - Visible Emission Spectrometry	7
	Infrared Spectrometry	6
	Sample Culture With pH Readout	6
	Alpha Scattering Spectrometry	6
	Differential Thermal Analysis	6
	Sample Culture With Radioisotope Readout	6
Origin, History, Age -- Earth-Moon System	X-Ray Diffraction	10
	Gamma Spectrometry	9
	Mass Spectrometry	9
	Neutron Activation Analysis	9
	X-Ray Fluorescence Spectrometry	9
	Alpha Ray Spectrometry	8
	Ultraviolet - Visible Emission Spectrometry	8
	Gas Chromatography	6
	Infrared Spectrometry	6
	Alpha Scattering Spectrometry	6

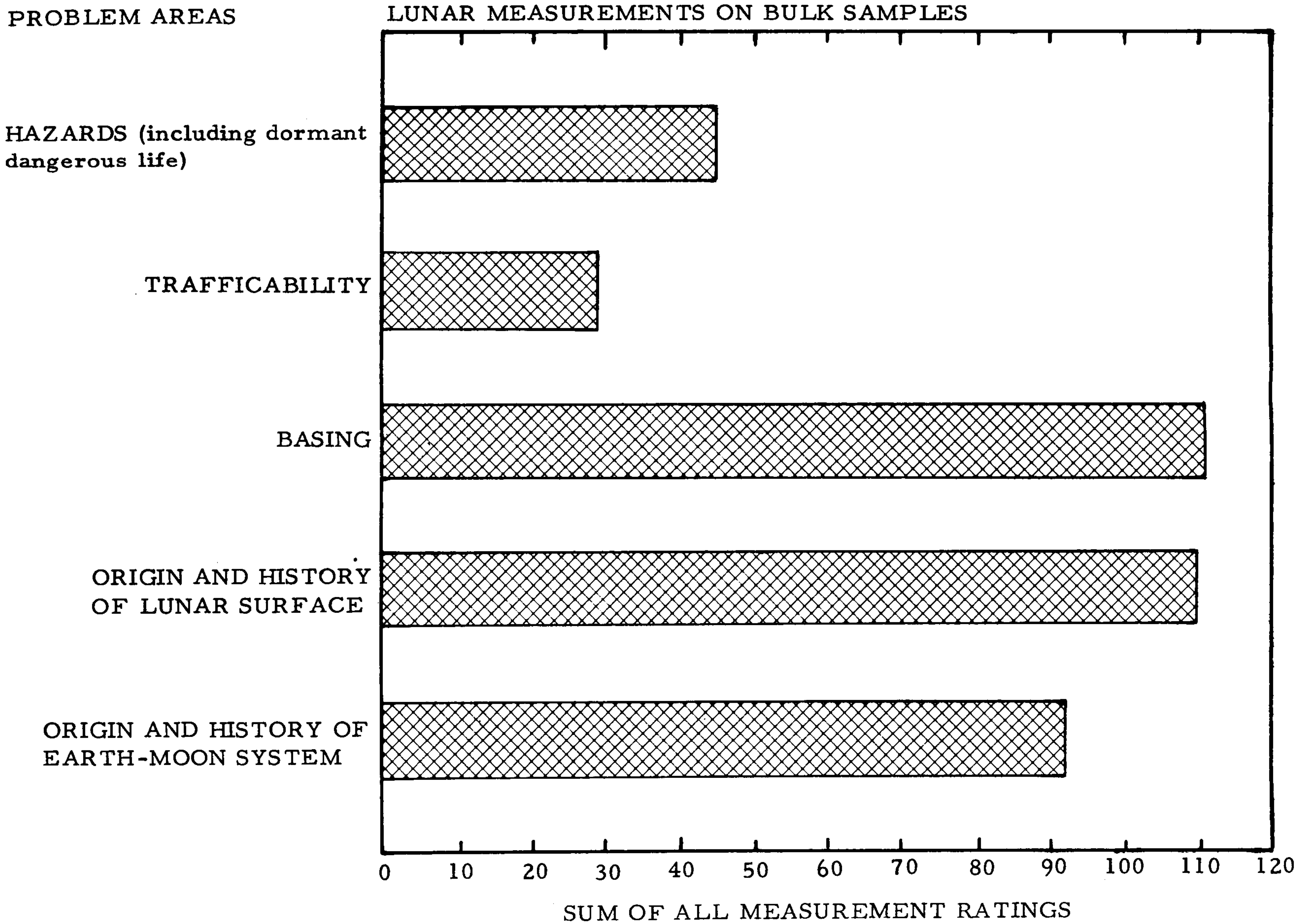

Figure I-9. Preliminary Estimate of the Relative Contribution of Compositional Measurements to the Fundamental Problem Areas.

3. Importance of Compositional Measurements and Observations

a. Hazards

Probably the most important compositional hazards are dormant potentially dangerous life forms and abnormally reactive ultra-clean surfaces. Reactive surfaces and space or lunar radiation hazards are discussed by Arthur D. Little, Inc. in the section on radiological measurements. The problem of possible dormant life forms and the less probable danger of corrosive gases from volcanic vents are considered below.

1) Dormant Potentially Dangerous Life Forms

There is considerable disagreement as to the possibilities of the existence of life forms on the moon. The literature of biology in space has been reviewed by Lederberg (1960), Horowitz (1962) and Seybold (1963).

The Committee on Contamination by Extraterrestrial Exploration concluded that the possibility of life persisting on the moon is sufficiently remote that it can be neglected. This is based on the assumption that there are no earth-type living cells that can grow or multiply in the absence of water and that, at the high vacuum of the moon, no water can exist on its surface (International Council of Scientific Unions, 1959; Hughes Aircraft Co., 1961).

The opposing view is presented by Firsoff (1959), Lederberg (1960) and Sagan (1961). Firsoff suggested the possible presence of local climates or atmospheres within walled enclosures, clefts and hollows and interpreted lunar colors in terms of possible low forms of living organisms. Lederberg believed the composition of layers below the moon's surface cannot yet be discounted as a possible location for a lunar biology even though the surface may be barren due to the absence of an atsmophere and to solar radiation exposure. Sagan concluded that a surface density of 1 to 10 gm/cm^2 of organic molecules could have been formed by ultraviolet radiation synthesis in the former primitive lunar atmosphere. Heat and further radiation could have modified the earliest simple structures and produced molecules of great complexity as the atmosphere was dissipated. If this were the case, there should be a buried zone of organic matter under some undetermined depth of surface debris. This material might be distributed throughout the debris layer and could contain dormant simple life forms.

Lunar temperature variation and vacuum conditions may not be sufficiently severe to destroy certain bacteria or spores if they are protected from the direct solar radiation. Becquerel (in Firsoff, 1959) has shown that mosses, lichens and algae can be immersed in liquid air (-109°C) for several weeks without harm and, when dry, for as long as six years. More surprising still, their dried spores retained full vitality after being plunged in liquid helium (-271°C) and exposed to vacuum. Some protozoa live permanently in hot springs at temperatures to 90°C and can withstand as much as 150°C for short periods when desiccated.

Most studies have been concerned with the problem of contaminating the moon biologically and thereby losing the opportunity to obtain significant information on such problems as the early history of the solar system, the distribution of life beyond the earth and perhaps even the origin of life itself (Sagan, 1961). These problems are discussed more fully in a later section. The reverse possibility of contaminating the earth with a new life form could be much more disastrous than the scientific losses in moon contamination. The most dramatic hazard would be the introduction of a new disease which humans are not capable of resisting. Lederberg (1960) believed this to be extremely unlikely since most disease-producing organisms must evolve elaborate adaptations to resist the defenses of the human body, to attack human cells and to pass from one person to another. It is quite unlikely for this to happen without experience with human hosts.

Even though the risk of pandemic disease is low, this possibility must be examined carefully and guarded against at all costs. Countermeasures involve detection of life forms, decontamination by sterilization of spacecraft, samples and space suits, and quarantine of returning lunar astronauts for a suitable period.

Experiments for the detection of life should be undertaken by unmanned missions utilizing microbiological probes prior to the APOLLO missions. If this is not done, APOLLO instrumentation should include a life detection device based on placing one or more lunar soil samples in a nutrient environment and observing any changes during the return trip to earth.

Organism growth detection can be based on microscopic observations or on instrumental readout in terms of pH change in the nutrient or radioisotopic detection of evolved carbon dioxide, etc.

Pyrolysis of samples followed by gas chromatography or mass spectrometry of the evolved gases can serve to detect complex molecules as indirect indicators of the presence of life forms.

Sterilization techniques under study for returning vehicles and instruments include employment of ultrasonics, radiation, dry heat, chemicals, cryogenics, dehydration, and mechanical devices. Complete and effective sterilization, as applied to outgoing vehicles and equipment without damage to components, is rather complex but considered feasible (Phillips and Hoffman, 1960; Wynne, 1961). Avoidance of damage is not so critical on returning vehicles and equipment and therefore should be accomplished more easily.

2) Corrosive Gases

The spectroscopic observations of Kozyrev (1959) on the central peak of Alphonsus and the visual observations of the Aristarchus region reported by Greenacre (1963) provide recent and strong evidence of occasional brief degassings of the moon. Other observations of lunar surface changes of a similar nature have been reviewed by Green and Van Lopik (1961).

While it is highly unlikely that the APOLLO astronauts will land at precisely the time or place of a major eruption visible from the earth, it may be that smaller fumarole-like features or vents are more common and a finite probability of encounter may be realistic. Such an occurrence would be the only likely source of an atmosphere and could be detected by some sort of pressure-measuring device such as an unenclosed ionization gauge which could be hand-held and read to indicate the anomalous presence of gases.

Fumaroles or volcanic vents on the moon would probably produce gases similar to true magmatic vapors. A review of the general subject of fumaroles, hot springs and hydrothermal alteration on earth has been given by White (1963), and a special treatment of the composition of volcanic emanations is presented by White and Waring (1963).

Fumarolic gases are known on earth to contain relatively large percentages of CO_2, $HC\ell$, HF, H_2S, SO_2, SO_3, and steam. The acid gases, $HC\ell$, HF, SO_2, and SO_3, in the presence of water could conceivably form corrosive acids on the surface of space suits, vehicles or equipment and seriously impair their operation if there were sufficient time of contact.

If the gases were detected by increase of pressure, they could be sampled and analyzed by gas chromatography to determine the presence or absence of possible corrosive constituents.

b. Trafficability

The contribution of compositional studies in this area is primarily in (1) density determination by gamma ray backscattering, and (2) in the more remote possibility that knowledge of the composition of surface material will contribute in predicting some of the trafficability problems likely to be encountered.

Density determination by gamma ray backscattering is included in this section because of the similarity of the detection equipment to that used in radiation hazard detection.

1) Density Determination by Gamma Ray Backscattering

In simple terms, this measurement involves a gamma radiation source and a detector unit which is shielded from direct source radiation but which can receive indirect backscattered radiation. The amount back-scattered is proportional to the density of material encountered and, with proper calibration, may be used for density measurement.

If material of very low density occurs on the lunar surface, it may be suspected of being in the form of rock foam or light dust. These materials might not be sufficiently strong to support men or vehicles without special designs for wheels or shoes.

2) Use of Compositional Knowledge in Trafficability Prediction

Certain clay compositions with sufficient moisture content on earth cause trafficability problems due to stickiness or low bearing strength. By analogy, compositional information for the lunar surface might contribute in predicting trafficability. Moist clay probably will not occur on the moon's surface, and the direct analogy is not applicable. But, until more definite knowledge of lunar conditions is available, it is felt that other mineral compositional relationships to trafficability may be found useful,so this possibility should be kept in mind. The X-ray diffractometer provides the most reliable information as to mineral composition in materials too fine-grained for visual identification.

c. Basing

The possible use of lunar materials as resources in base construction and support is of prime importance and has been the subject of special studies by Green (1962, 1963) and the Working Group on Extra-terrestrial Resources Committee (Johnson, 1963).

Composition measurements can provide valuable information to identify these resources and to predict their probable occurrence based on geological and geochemical principles. Certain compositional instruments also are capable of providing information bearing on foundation problems in base construction and radiation shielding requirements.

1) Foundation Problems

The nature of the surface materials and bedrock may be determined by mineralogical or chemical composition measurements where visual identification may not be possible due to fine grain size or other special lunar difficulty. X-ray diffraction, differential thermal analysis and infrared spectrophotometry may be used in mineral determinations. Gamma ray spectrometry, X-ray fluorescence spectrometry, neutron activation analysis, ultraviolet-visible emission spectrometry, and alpha scattering spectrometry may be used to find elemental composition. Detection of characteristic mineral and/or elemental assemblages will allow rock-type identification and help in predicting engineering geologic behavior.

Under certain conditions, the gamma ray spectrometer may prove useful in detecting concealed faults which might cause foundation problems through renewed movement. It has been found that faults and other major fracture may act as channelways for the diffusion of radon gas to the surface (Sikka, 1962; Simpson, 1963). Radon is a relatively short-lived daughter product of uranium which is found in concentrations on the order of parts per million as a normal impurity in rocks. The radon in turn has a strong gamma ray emitter, Bi^{214}, as a daughter, and this usually will be detected in larger than normal quantities in the immediate fault region.

The gamma ray backscatterer may be used to measure surface density and thereby detect areas of low surface strength because of light dust accumulation or rock froth.

2) Radiation Shielding

The gamma ray backscatterer can be used to good advantage to test lunar radiation shielding materials. This can be done by detaching the radiation source and interposing the material to be tested between it and the detector unit under conditions of controlled geometry. Shielding efficiency can be calculated by dividing the difference in counting rate with and without the material interposed by the thickness of the sample.

This instrument also can be used for its normal density determination on unknown shielding material, and the effective shielding efficiency can be estimated assuming it to be directly proportional to density.

3) Volatile Resources

Volatile resources include such materials as water, oxygen, hydrogen, and various volcanic gases either in the free state from fumaroles or combined with rocks or minerals in thermally releasable forms.

Water is considered one of the major important resources (Salisbury, Glaser and Wechsler, 1963; Speed, 1963). Methods considered for water deposit exploration on the moon include those based on differences in density, mineral composition, radioactivity, electrical conductivity, acoustic velocity, neutron logging response, and response to multiband remote sensing (Green, 1960; Van Lopik and Westhusing, 1963).

These deposits might include ice or hydrated rocks or minerals. Compositional methods of directly detecting and measuring water content would include differential thermal analysis, gas chromatography, mass spectrometry, neutron logging methods, etc. Probably the most effective method would involve differential thermal analysis to detect the temperatures of dehydration of samples. Gas chromatographic analysis of the volatile products would be used to determine quantitatively the amounts of water available.

Poole (1963) discussed the possibility of obtaining oxygen from the thermal dissociation of oxides of silicon, aluminum, magnesium, and related materials, if these are found in the lunar crust as they are on earth. A similar apparatus utilizing a very high-temperature furnace with a gas chromatograph could be used to analyze for the oxygen evolved. Any other volatiles in the rocks could be measured at the same time using this type of equipment.

The detection of fumaroles or volcanic gas vents with a pressure gauge and their evaluation as sources of water, CO_2, $HC\ell$, HF, H_2S, SO_2, and SO_3, by gas chromatrography were considered in the foregoing under hazards.

The mass spectrometer also can be used for volatiles in the free state or even in combined form if a suitable ion source is used.

Neutron logging techniques should be particularly useful in detecting free water or ice deposits based on the high neutron scattering cross-section of the hydrogen nucleus (Green, 1960).

4) Solid Resources

Solid resources of possible lunar occurrence and use in lunar base construction or support include iron-nickel meteorites, chondrites, pumice, basalt, other possible dimension stone or aggregate, sulfur and other volcanic sublimates, and hydrothermal vein materials. Many of these may be difficult to recognize by visual or hand tests under the difficult conditions of lunar exploration, and instrumental methods of compositional testing may be useful for identification. X-ray diffraction, X-ray fluorescence and neutron activation analysis should be valuable in this regard.

The known principles of geochemistry in igneous differentiation may be used to predict possible ore deposits. For example, the presence of certain rock types such as granites or rhyolites indicates that igneous differentiation has occurred, and it is quite likely that certain types of hydrothermal ore deposits might be found nearby. It is beyond the scope of this work to go into detail as to the types of ore associated with specific rock types, but this information is available in standard texts and reference books such as Bateman (1950) and the Lindgren Volume (Finch, ed., 1933).

Careful analysis and interpretation of the first APOLLO samples returned to earth will provide the very important first step to judge the possibilities of using lunar materials for base construction and support. The primary utility of compositional tools on the moon's surface will come later when longer stay times and increased mobility permit exploration of larger areas.

Trace analysis of lunar surface samples may be useful as a guide to possible concealed mineral deposits. Hydrothermal deposits often have a "halo" or zone of abnormally high metallic element content surrounding them for some distance. This primary geochemically anomalous region is much larger than the visible ore mineralization and therefore easier to find when systematic sampling patterns are employed. Hawkes and Webb (1962) summarized this approach to minerals prospecting on the earth. It is quite possible that modifications of the analytical procedures suitable for lunar application could be developed utilizing emission spectrometry, gamma ray spectrometry or other trace element techniques.

d. Origin and History of Lunar Surface

The mode of origin and the history of lunar materials have determined their present composition and therefore, analysis of the composition provides a starting place from which to work backward to interpret lunar history. The information gained from the first few lunar samplings and observations will be a tremendous step forward from our present status of knowledge. However, experience in interpreting earth history has shown that many more steps will be required before the fundamental questions of origin and history are answered to the satisfaction of the majority of scientists.

1) Composition of Soil and Bedrock

Two major theories for the origin of the larger lunar surface features contend that they are due to either volcanic activity or meteoritic impact. These theories would imply different mineralogical and chemical compositions for the majority of the surface samples and could be differentiated instrumentally based on:

- Mineral content by X-ray diffractometer
- Major chemical element content by X-ray spectrometer, neutron activation analyzer, alpha scattering spectrometer, etc.
- Minor chemical element content by gamma ray spectrometer, ultraviolet and visible emission spectrometer, or neutron activation analyzer

Further details on the compositional implication of the various theories of lunar origin are given in the next section of this chapter.

2) Composition and Extent of Lunar Atmosphere

Most available information leads to the conclusion that the lunar atmosphere is extremely tenuous ($< 10^{-13}$ torr) and, therefore, impossible to sample and analyze adequately with present state-of-the-art equipment. It is highly probable that the contamination from rocket exhaust gases will be the most important constituent to be found in the immediate landing area. It probably will not be possible for astronauts to travel far enough to be sure that this problem is avoided in sampling during early APOLLO missions.

One method to obtain valuable information in this problem area would be to leave an atmospheric pressure measuring instrument behind in the Scientific Instrument Package (SIP). The loss of rocket gas contamination through diffusion could be followed as a function of time after the LEM leaves until the normal atmospheric pressure again is reached. The instrument for this use could be a modification of a magnetron ionization gauage or similar device.

Measurements with such an instrument could be made by the astronaut during traverses of the surface to detect any local or temporary atmospheres that might occur due to degassing of the lunar interior.

3) Absolute Age Determinations

Age measurements are of singular importance in unravelling the history and origin of lunar features. In the first APOLLO missions it will be necessary to perform such determinations on samples returned to earth.

The usual techniques of K-Ar, Rb-Sr and U-Pb undoubtedly will be used. Recent developments in those techniques have been reviewed by Tilton and Hart (1963), Hart (1963) and Hamilton, Dodson, and Snelling, 1962). They have been found generally adequate for most geologic age problems, and experimental techniques have undergone little change in the past few years.

Table I-4 presents a brief review of the parameters involved in the four major systems which have been found to be widely applicable (Kulp, 1963).

TABLE I-4

MAJOR METHODS IN GEOCHRONOMETRY

(After Kulp, 1963)

NUCLIDES	HALF LIFE (YR)	λ (YR $^{-1}$)	EFFECTIVE RANGE (YR)*	MATERIALS
U^{238}-Pb^{206}	4.5×10^{9}	1.54×10^{-10}	10^{7}-T_{o}	zircon, uraninite, pitchblende
U^{235}-Pb^{207}	0.71×10^{9}	9.72×10^{-10}	10^{7}-T_{o}	zircon, uraninite, pitchblende
Rb^{87}-Sr^{87}	4.7×10^{10}	1.47×10^{-11}	10^{7}-T_{o}	muscovite, biotite, lepidolite, microcline, glauconite, whole metamorphic rock

TABLE I-4 (CONTD)

NUCLIDES	HALF LIFE (YR)	$\lambda (YR^{-1})$	EFFECTIVE RANGE (YR)*	MAIERIALS
$K^{40}-Ar^{40}$	1.30×10^{9} (total)	$\lambda\beta\ 4.72 \times 10^{-10}$ $\lambda e\ 5.83 \times 10^{-11}$	† $10^{5}-T_{o}$	muscovite, biotite, hornblende, phlogopite, glauconite, sanidine, whole volcanic rock, sylvite (arkose, sandstone, siltstone)**
C^{14}	5710 ± 30	1.21×10^{-4}	0-50,000	wood, charcoal, peat, grain, tissue, charred bone, cloth, shells, tufa, ground water, ocean water

*T_{o} = age of the earth, i.e., $\sim 4.6 \times 10^{9}$ yr
**For paleogeographic studies
† Under certain favorable conditions, the lower limit of this method can be extended to approximately 10^{4} yr

In general, the Rb-Sr and K-Ar methods may be used on some of the major mineral constituents as shown and the U-Pb methods on zircons in the heavy mineral separates from igneous rocks.

Newer methods of age determination include thermoluminescence methods (Zeller and Ronca, 1962), and fission track counting (Sippel and Glover, 1964) as applied to calcites. Fission track counting shows the most promise of practical application to lunar problems. It was first applied to mica crystals by Price and Walker (1963) and later to tektites and ancient glasses by Fleischer and Price (1964). Most of the tektite results were in good agreement with K-Ar measurements. Evidence indicates that the fission tracks can anneal and disappear at high temperatures. Further work in this area may lead to methods of studying the thermal history of lunar specimens.

Material in space is exposed to cosmic radiation, and nuclear reactions are induced in the meteoritic matter. The reaction products can be measured to yield information on the exposure ages of meteorites. New developments in this area have been reviewed by Signer (1963). Information on the cosmic ray exposure of the lunar surface could be obtained by applying these measurements to lunar samples.

e. Origin, History and Age of Earth-Moon System

Several major hypotheses have been presented to explain the origin of the moon. These include (1) cold meteoritic accretion with or without later radioactive heating, (2) cooling and solidification of a molten body and (3) gravitative capture of a large planetoid and even a catastrophic tidal separation from the Pacific Ocean basin. Each theory implies a particular set of rock compositions for the maria, the craters and the highlands of the moon.

1) Elemental Compositional Implications

Palm and Strom (1962) summarized the mode of formation of the lunar features as presented by prominent lunar scientists (Table I-5). The possible elemental abundances implied by these hypotheses are shown in Table I-6 .

In addition to these rock types, there is the possibility of occurrence of sediments if the moon originated by tidal separation from the earth.

Proper identification of all rock types on the moon is of paramount importance to sort out the proper hypotheses of origin. If visual or hand methods fail due to difficult lunar conditions, it may be necessary to resort to instrumental methods.

The most detailed approach is to analyze for the major elements in the rocks by X-ray spectrometry, emission spectrometry, neutron activation analysis, or mass spectrometry and, on this basis, identify the types present. Another instrumental approach might use the X-ray diffractometer to identify characteristic minerals present and thereby determine the rock type.

As a first approximation, the problem may be reduced to the determination of three broad rock types as shown in Table I-7 (Palm and Strom, 1962).

These are igneous rocks of acidic (high silica), basaltic (medium silica) and meteoritic (aerolitic) compositions. Comparison of the characteristic elemental abundances illustrates the ease of identification of general rock type on the basis of chemical composition.

TABLE I-5

MODE OF FORMATION OF LUNAR SURFACE FEATURES

(After Palm and Strom, 1962)

Investigator	Maria	Major Craters	Rays	Domes	Ridges	Valleys	Rills
Baldwin	Impact-Extrusion	Impact	Impact-Ejecta	Volcanic	Solidified Lava Waves	Secondary Impact Gouges	Tension Cracks
Firsoff	Plutonic-Extrusion	Volcanic	Snow in Tension Cracks	Volcanic	Compression Ridges	Grabens	Tension Cracks
Gold	Impact-Nonmelting	Impact	Impact-Ejecta			Secondary Impact Gouges	Istostatic Adjustments
Kuiper	Impact-Extrusion	Impact	Impact-Ejecta	Volcanic	Compression Ridges	Secondary Impact Gouges and Grabens	Tension Cracks
Spurr	Plutonic-Extrusion	Volcanic	Volcanic-Ejecta	Volcanic	Compression Ridges	Grabens	Tension Cracks and Fault Fissures
Urey	Impact-Melting	Impact	Impact-Ejecta	Volcanic	Dust Hills	Secondary Impact Gouges	Tension Cracks

TABLE I-6

POSSIBLE ELEMENTAL ABUNDANCES CORRESPONDING TO EACH HYPOTHESIS
(After Palm and Strom 1962)

Hypothesis	Gold		Urey		Kuiper		Baldwin		Spurr		Firsoff	
Element	Maria[1]	Terrae[2]	Maria[3]	Terrae[4]	Maria[5]	Terrae[6]	Maria[7]	Terrae[8]	Maria[9]	Terrae[10]	Maria[11]	Terrae[12]
O	20-45	33-44	43-46	33-44	47-52	47-51	43-46	48-52	44-46	48-52	48-55	48-55
Si	10-22	17-25	21-24	17-25	32-38	31-35	21-24	31-35	22-24	33-35	33-36	33-36
Al	0.5-2	1-6	4-9	1-6	5-9	6-10	4-9	6-10	8-10	6-9	6-9	6-9
Fe	15-40	12-22	8-11	12-22	1-6	1.5-4	8-10	1-5	6-9	1-3	1-3	1-3
Mg	8-18	14-18	3-15	14-18	0.2-2	0.1-1	3-15	0.1-1	3-5	0.2-0.8	0.2-0.8	0.2-0.8
Ca	0.2-2	1-7	5-8	1-7	0.1-2	1-3	5-8	0.3-3	6-8	0.2-3	0.5-2	0.5-2
Na	0.3-1	0.6-0.8	0.5-3	0.6-0.8	0.2-4	2-4	0.5-3	2-4	1.5-2.5	2.5-4	2-4	2-4
K	0-0.1	0.1-0.2	0.2-2	0.1-0.2	1.5-4.5	2-4	0.2-2	1.5-4.5	0.5-1.5	2-4	2-4	2-4
H	0.1-0.3	< 0.3	0.1-0.3	0.1-0.3	0-0.2	0-0.2	0.1-0.3	< 0.2	0.1-0.3	0.1-0.3	0.5-1.2	0.1-0.3
C	< 1	1-5	1-3	3-11	< 1	< 1	< 1	< 1	< 3	< 3	< 3	< 3
S	0-3	0.2-3	< 0.5	0.2-3	< 1	< 1	< 1	< 0.5	0-6	0-6	< 1	< 1
Ni	0.1-3	0.1-2	< 0.5	0.1-2			< 0.05	< 0.5				

1. Chondritic Dust
2. Aerolitic
3. Basaltic
4. Chondritic
5. Rhyolitic
6. Acidic
7. Basaltic
8. Acidic
9. Basaltic
10. Rhyolitic
11. Rhyolitic
12. Rhyolitic

TABLE I-7

ELEMENTAL ABUNDANCES (PER CENT BY WEIGHT)

(After Palm and Strom, 1962)

		MARIA AND TERRAE	
ELEMENT	ACIDIC	BASALTIC	AEROLITIC
O	47 - 52	43 - 46	33 - 44
Si	31 - 38	21 - 24	17 - 25
Al	5 - 10	3.5 - 9	1 - 6
Fe	1 - 6	6.5 - 10	12 - 22
Mg	0.1 - 2	3 - 14	14 - 18
Ca	0.1 - 3	5 - 8	1 - 7
Na	0.2 - 4	1 - 2.5	0.6 - 0.8
K	1 - 5	0.2 - 1.5	0.1 - 0.2
Ni			0.1 - 1.7
S			0.2 - 2
H	0.7 - 0.2	0.1 - 1	0.03 - 0.1

2) Radioelement Compositional Implications

Characteristic minor element contents also may be used to identify rock types. Of these, natural radioactive elements provide the advantage of field analysis by means of gamma ray spectrometer.

In general, the uranium, thorium and potassium contents of igneous rocks increase with increasing acidity or silica content. Thus, the granites have the highest average contents, with intermediate amounts in basalts and gabbros and lowest average amounts in ultrabasic rocks such as peridotites. Table I-8 shows concentration ranges generally found in these igneous rocks. Chondrites (stony meteorites) are similar to the ultrabasic intrusives shown.

The K^{40} isotope makes up a constant portion of natural potassium (0.0119 per cent) and, therefore, its radioactivity is directly proportional to the content of K_2O as listed.

TABLE I-8

THORIUM, URANIUM AND POTASSIUM IN IGNEOUS ROCKS

Rock	Thorium** (in ppm)	Uranium* (in ppm)	Potassium** (in % K_2O)
Silicic Intrusive (Granites, Syenites)	1 - 25	1 - 6	1.5 - 6.0
Silicic Extrusive (Rhyolites, Trachytes)	9 - 25	2 - 7	
Basic Intrusive (Gabbros, Diabases)	0.5 - 5	0.3 - 2	0.4 - 3.0
Basic Extrusive (Basalts, Andesites)	0.5 - 10	0.2 - 4	
Ultrabasic Intrusives (Peridotites, Dunites)	low	0.001 - 0.03	0.1 - 1.0

*Adams et al., 1959
**Daly, 1933

The concentration ranges shown in Table I-8 reflect the tendency of uranium, thorium and potassium to accumulate in the residual fluids as a rock melts or magma crystallizes. The following course of magmatic crystallization has been offered to explain the observed distribution of uranium and thorium (Adams, Osmond and Rogers, 1959).

(a) Early crystallizing minerals, such as olivine from basic magmas, incorporate almost no throium or uranium and, consequently, the ultrabasic rocks have almost none.

(b) Among normal basic rock minerals such as pyroxene, calcic plagioclase and apatite, the latter may incorporate small amounts of uranium and thorium but not to a marked degree of concentration.

(c) The last silicic magmas carry the majority of the uranium and thorium and produce granites to tonalites with significant amounts of radioactivity concentrated in accessory minerals such as allanite, monazite and xenotine. Variable amounts may be fixed in the major minerals as inclusions or along-the-grain boundaries and fractures. Some of the very late-stage hydrothermal fluids may escape to form hydrothermal veins, pegmatites or lamprophyres (Emmons, Reynolds and Saunders, 1953).

(d) Potassium is a major constituent of the magma and is contained largely in the late-forming potash feldspars. It does not easily enter the lattice of the early-forming minerals and is, therefore, generally concentrated more in the silicic rocks. Further details on the potassium content of igneous rocks are given by Ahrens, Pinson and Kearns (1952).

These differences may be used to help identify the rocks present and classify them generally as acidic, basic or chondritic. The differences between intrusive and extrusive phases of the same type are not large enough to be diagnostic. A further advantage of the gamma spectrometer is that the same instrumentation may be used for neutron activation analysis merely by adding a suitable neutron source. This will greatly extend its analysis capability.

3) Other Minor Elements

The emission spectrometer and neutron activation analyzer can be used to search for other characteristic nonradioactive minor element combinations. General references as to the geochemical behavior of these elements include Green (1959), Mason (1958), Goldschmidt (1954) and Rankama and Sahama (1950).

4. Problems Associated With Compositional Measurements and Experiments

a. Instrument Design

The most fundamental problem is the difficulty in obtaining good compositional information using the simplified instrumentation necessary to fit within the weight, volume and power constraints of early APOLLO missions. Compositional measurements generally are performed in the laboratory rather than in the field, and most lunar "field" equipment must be specially designed without benefit of much prior earth field equipment experience. This may be contrasted with geophysical and geological field equipment which has benefitted by many years of earthbound field development. Most lunar compositional instrument designs can be expected to have more "bugs" than those of some of the other disciplines.

b. Safety Considerations

In addition to hazards common to all field operations, those of the compositional instruments involve heat and energetic radiation sources which must be considered astronaut safety factors.

1) Radiation Hazards

The sample culture experiment with radioisotope readout would involve carbon-14 or possibly tritium and sulfur-35. These are all beta emitters with relatively small radiation hazard unless ingested or present in large quantities.

Gamma ray backscattering, X-ray diffraction, neutron hole logging, X-ray fluorescence spectrometry and neutron activation analysis involve potential hazards from penetrating radiation sources. In all these, proper shielding must be used and the astronauts trained in safe handling procedures.

The alpha-scattering spectrometer will contain an alpha source suitably contained to prevent escape of the alpha emitter in any manner that might allow accidental ingestion by the astronauts. Alpha radiation is not very penetrating and does not present a radiation hazard if contained by 1 mm or so of aluminum. Burns may result if the radiation falls directly on the skin.

2) Thermal Hazards

The gas chromatograph, differential thermal analyzer, mass spectrometer, UV-visible spectrometer, and infrared spectrometer normally contain a heat source which must be shielded to prevent contact with and thermal decomposition of the astronaut or his suit. Since normal instrument designs usually take this problem into account, it should be of minor concern.

3) Electrical Hazards

The usual electrical insulation problems will be involved in all instruments using electrical power, especially those utilizing high voltages -- accelerator-type neutron generators, mass spectrometers and X-ray sources.

5. Instrumentation for Compositional Measurements

a. Procurement of Information

The April 1963 Buyers Guide issue of Analytical Chemistry was surveyed for all possible analytical instrument types, and 95 letters were written to significant instrument makers requesting brochures of their present instruments, both laboratory and space types, and of any development work on a space model. There were 62 replies which are summarized as follows:

19	No help
30	Some help
9	Very helpful
4	Excellent (described space instruments)

Company descriptive literature was received on the following instruments:

Mass spectrometers	Recording thermometers
Gamma ray spectrometers	Radiation detectors
Emission spectrographs	Gross beta counters
Neutron activation analyzers	Gross alpha counters
Beta spectrometers	Gross gamma counters
X-Ray diffractometers	Alpha activation analyzers
X-Ray spectrometers	Neutron backscatter equipment
Electron microprobe analyzers	Interferometers
Gas chromatographs	Microscopes
Infrared spectrometers	Hand telescopes
UV-Visible spectrometers	Beryllium detector
Balances	Smoke and dust photometer
Pyrometers	Polarimeters
Thermocouples	Refractometers
Nuclear magnetic resonance equipment	Differential thermal analyzers

Brochures on several types of instruments, such as temperature measuring devices, interferometers, microscopes, and polarimeters, were given to other study groups directly concerned with them.

All available reports on space instruments were examined. These included JPL Space Program Summaries, reports from other National Aeronautics and Space Administration sponsored organizations, and journal articles.

One trip was made to California on Feb. 24-27, 1964 to talk with scientists at Jet Propulsion Laboratory, and with Consolidated Electrodynamics Corp. and Beckman Instruments.

b. Evaluation of Space Instrumentation

All instruments which were designed for space use and could be used for compositional analysis contained in these reports were evaluated for possible use on the moon. All of the Surveyor instruments were especially noted, since they were designed to operate on the moon. These instruments were evaluated according to weight, power, volume, sensitivity, dynamic operating range, operating time, and setup time.

All of the Surveyor instruments need modification to operate on or with the APOLLO spacecraft. For some, only minor modifications, such as power and telemetry matching, would be necessary. For others, major modifications may be necessary, particularly where a change in experiment complexity (either more or less) is advantageous. Certainly, an instrument that operates satisfactorily on Surveyor could be converted with some modifications to operate on APOLLO.

The space model instruments evaluated are:

Gas chromatograph	Beckman Instruments, Inc.
UV-Visible spectrometer	Beckman Instruments, Inc.
X-ray diffractometer	Philips Defense & Space Laboratory (Norelco)
X-ray spectrometer	Philips Defense & Space Laboratory (Norelco)
Neutron activation analyzer	JPL, Sandia, Lawrence Radiation Lab
Gamma ray spectrometer	JPL design
Gamma ray backscattering device	JPL design
Alpha particle scattering spectrometer	Professor Turkevich. Univ. of Chicago
Mass spectrometer, Goddard satellite type	Consolidated Electrodynamics Corp.
Life detectors	Hazelton Labs; California Institute of Technology, JPL

c. Evaluation of Laboratory Instrumentation

Many brochures of commercial laboratory instruments were received covering all instrument types and rated as shown on the preceding page. These laboratory-type instruments are large and heavy compared to their space counterparts but do show the best operating characteristics or capabilities of each instrument type. On that basis, representative lab instruments including one or two of each type were evaluated on the same basis as the space types. In general, direct comparisons cannot be made between laboratory and space types. In some instances, design considerations for a space type severely limited its range or changed the method of obtaining the data from its laboratory counterpart.

Laboratory instruments need evaluation for yet another reason -- to determine their capabilities for analysis of lunar samples brought back to earth. An excellent up-to-date summary of recent developments in all analytical techniques is presented in the April 1964 Annual Review issue of Analytical Chemistry.

d. Summary of Space Instruments

In general, the space instruments are extremely well built and engineered. Of the Surveyor I type instruments, the gas chromatograph and the X-ray diffractometer compare favorably with their laboratory counterparts. Hence, these are the best of the group and, with necessary modifications, will be prime candidates for APOLLO. The X-ray spectrometer will be in the same group if detail design problems can be resolved. The mass spectrometer and neutron activation analyzer are severely restricted by power limitations and fall far short of their laboratory counterparts. However, recent development work indicates that each can be significantly improved in the next models. The UV-visible spectrometer for elemental analysis, built by Beckman, is a hybrid instrument covering several types: flame photometry, UV-visible absorption and emission spectrometry. This spectrometer performs its design job very well and probably could be developed into a useful lunar instrument for APOLLO. The Alpha particle scattering spectrometer is a new type of analytical instrument designed by Professor Turkevich at the University of Chicago and has no lab counterpart. It has a restricted mass range (up to Fe, Ni) and may have only limited usefulness in a general mixture of minerals, but it is the only analytical-type instrument for compositional analysis that remains on the Surveyor I payload. The gamma ray spectrometer is not nearly as good as the laboratory type, mainly because of severe volume limitations. However, the field of miniaturization is advancing rapidly, and it is quite possible that a good 512-channel analyzer can be developed within a few years. The gamma ray backscattering instrument for density measurement is a fairly well-developed device that with modest modifications, should perform well on early APOLLO missions.

e. Equipment and Instrumentation for Compositional Studies

Instruments considered most useful for lunar compositional studies were selected on the basis of (1) mission constraints, (2) contributions to fundamental lunar problem areas and (3) instrumentation state-of-the art. Instruments proposed for use on early APOLLO missions are:

- Life detector with pH readout
- Life detector with radioisotope readout
- Gas chromatograph
- X-ray diffractometer
- Gamma ray spectrometer
- Mass spectrometer
- Differential thermal analyzer
- Neutron activation analyzer
- X-ray fluorescence spectrometer

6. Ranking of Compositional Measurements, Observations and Experiments

More than 40 instruments to perform compositional measurements were evaluated and an equally large number of experiments and observations examined. Careful consideration was given mission constraints and potential contributions to astronaut safety, lunar trafficability and basing, and to knowledge of the lunar surface and the earth-moon system. It is concluded that the following measurements and experiments, listed in approximate order of importance, can be advantageously undertaken on the moon:

- Determination of potentially dangerous life forms. Use sample culture with pH or radioisotope readout. Pyrolysis of samples followed by gas chromatography or mass spectrometry of evolved gases could be used to detect complex molecules as indirect evidence of life forms.

- Detection and measurement of water content. In determining mineral and chemical composition of rock materials, hydrated rocks and minerals may be discovered. Differential thermal analysis, gas chromatography and mass spectrometry can be applied.

- Radiation shielding materials. Determinations can be made on samples returned to earth, but the procedure using a gamma ray backscatterer described earlier provides an excellent alternate.

- Mineral and chemical composition of rocks. The following instruments can be used: X-ray diffractometer, X-ray spectrometer, differential thermal analyzer, gas chromatograph, gamma ray spectrometer, and mass spectrometer.

- Radioisotopic composition. Gamma and alpha ray spectrometric measurements on lunar samples can be made.
- Stable isotopic composition. Mass spectrometry and neutron activation analysis can be applied.
- Lunar atmospheric pressure measurement. Determination of normal pressure can be made with magnetron ionization gauge or similar device.
- Density of soil and surficial material. Density determinations can be made with a gamma ray backscatterer.

G. RADIOLOGICAL MEASUREMENTS*

1. Introduction

a. General Statement

High-energy portions of the electromagnetic spectrum including X-rays, gamma rays, ultraviolet rays, and particulate radiation as well as induced lunar radioactivity are the phenomena examined in this section. Consideration is given measurements and instruments that might be used to solve radiological problems during a lunar landing. Emphasis is placed on hazards to astronauts and the effects of ionizing radiation on scientific equipment. Because the vehicle will not be nuclear-propelled, it will not by itself present a radiological hazard. Radiological problems during the trip to and from the moon are not pertinent to this study. As a guide to whether an experiment should be undertaken on the surface of the moon, it was assumed that, if the experiment or measurement could be made equally as well in an earth or lunar orbit, it should not be made during an early lunar landing.

b. Acknowledgments

Several of the topics in this section were discussed with Dr. H. S. Bridge and Dr. R. D. Evans of the Massachusetts Institute of Technology, Dr. W. C. Lin of the University of Iowa, and Dr. W. R. Webber of the University of Minnesota. Their contributions to this study are gratefully acknowledged.

c. Organization of Radiological Section

Because of the emphasis on astronaut hazards in early APOLLO missions, the various types of incident radiation on the moon's surface and the hazards they may constitute are discussed first. This is followed by an examination of several radiation-produced phenomena. Measurements, experiments and observations rated as important, reasons for their selection, and problems in making the observations are evaluated. Finally, the instrumentation required for the radiological studies is presented and the measurements and observations ranked relative to their importance in lunar exploration.

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*Contribution of A. D. Little, Inc., Cambridge, Mass.

2. Direct Radiation and Associated Hazards

Radiation in various forms, originating mostly from the sun, under certain conditions can cause biological harm to astronauts and equipment during a lunar landing. Radiation hazards in space flight have been estimated by many authors (USAEC, 1962). Generally, it is agreed that infrequent major solar flares are the principal direct hazard. Other forms of radiation probably are negligible, provided favorable conditions can be achieved.

The integrated dosage considered the maximum permissible for an astronaut during a lunar mission is not officially established. The general implication (Nickson, 1962) is that a dose in the range of 100 rads would not seriously reduce the astronaut's efficiency and would not lead to failure of the mission. A dose as high as 250 rads whole-body radiation might be possible, though only in cases of extreme exposure. Since the overall dose anticipated during a few-day lunar mission (excluding an unlikely major solar flare) is not over a few rads, the seriousness of the (nonflare) radiation hazard is low. Confirmation of the overall low level of radiation in space is found in flights such as that of the Mariner II to Venus in which only about 3 rads were measured during the 129-day mission (James, 1963).

In any event, hazards during lunar landing are expected to differ from those encountered during flight to and from the moon, only because of the difference in elapsed time for the two portions of the mission, the difference between radiation in free space and that on or near the moon's surface (which varies with its position relative to the sun), and difference in shielding afforded by the vehicle and the moon's mass. Particular attention is given factors influencing a lunar-landing operation rather than a trip to and from the moon. The following forms of radiation must be considered.

a. Ultraviolet Light

Although nonionizing ultraviolet light is not considered a radiological hazard, it is mentioned here for the sake of completeness. The ultraviolet radiation dose rate from full sunlight in space (which is rich in shortwave UV) far exceeds tolerable limits for white human skin. Fortunately, shielding from ultraviolet light is a very simple matter, well within the capability of any space suit. It is only necessary that the suit material be opaque to ultraviolet light.

The helmet visor must be transparent to visible light and essentially opaque to UV, but this condition is satisfied by several mechanically suitable plastics, such as polymethylmethacrylate and polycarbonates. Additives such as hydrozybenzophenones can be incorporated in the plastic to reduce further the UV transmission if necessary and to decrease the rate of discoloration of the polymer.

Effect of surface heating of space suits and equipment by ultraviolet light is similar to that with visible and infrared radiation. It is worth noting, however, that the means used for temperature control, such as selecting surfaces with proper absorptivity and emissivity properties, should take into consideration the high ultraviolet content of sunlight on the moon's surface. More information on ultraviolet light in solar radiation is needed, but no particular advantage is seen for measuring ultraviolet on the moon's surface.

b. Solar X-Rays

X-rays in space are so soft and are apparently present at such a low intensity (Vette, 1961) as to cause no hazard. For example, a few millionths of an erg per square centimeter per second is roughly equivalent to only a microrad per hour. X-ray intensity increases during a solar flare constitute only a small part of the hazard of solar flares and can be neglected. More data on X-rays in solar radiation are needed for scientific reasons. There appears to be little advantage, however, in measuring X-rays at the moon's surface rather than in an orbiting satellite.

c. Solar Wind

The continuous but varying stream of electrons, protons and heavier particles flowing from the sun is sufficiently low in energy to cause no direct hazard to astronaut or equipment in a few-day mission. Although surface "skin" dose rates might be in the range of 10^9 rads/hr (corresponding to a flux of 10^{11} protons/cm^2 sec with energies in the range of 0.1 Mev, having a range of about 1 micron in water), the soft radiation (e.g., a few kilovolt protons) is essentially completely shielded by a space suit of 1 to 2 gm/cm^2. Measurements on the moon of solar wind particles during lunar day and night would be scientifically interesting because of the possible effect of the solar wind in producing a lunar magnetic field. The field strength in the vicinity of the earth from the solar wind is about 2×10^{-5} gauss (Blanco and McCuskey, 1961).

d. Solar Flares

Major solar flares present a definite radiological hazard. Protons and alpha particles with secondary neutrons and gamma rays generated by proton interaction with the shielding are the most hazardous components of the flares. Doses received by a man protected only by a space suit of 1 or 2 gm/cm^2 could be fatal, while shielding of 5 gm/cm^2 would reduce the dose in the most extreme event to less than 135 rads (Freier and Webber, 1963). The frequency of occurrence of major flares varies over the 11-yr sun spot cycle from a maximum of about once each month for low-energy events to an average of once every 4-1/2 yr for high-energy events which give doses in the hundreds of rads through 1 gm/cm^2 spherical shielding (H_2O). Shielding in a space vehicle (to provide, say, 5 gm/cm^2) is difficult and, in a space suit, is virtually impossible for the high-energy events. The best solution is to plan missions during periods of the sun-spot cycle when flares are not at a maximum and to develop means of making short-range predictions of solar flares.

In contrast to the solar-cap absorption, there is a definite tendency for flares producing a large flux of protons in the 30-100 Mev range to occur during the increase and decrease of sun spot activity rather than during the maximum (Solar Proton Manual, 1963). If so, the statistical expectation of periods of peak hazard would be centered approximately in 1966 and in 1970 with an expectation of dangerous outbursts more frequent than once in 18 months; in 1968, the expectation is probably less than one dangerous burst per 18 months.

A large important cosmic-ray event is almost equally probable from the western or eastern hemisphere of the sun, and the probability appears higher from the sun's northern hemisphere. Average initial delay from time of peak optical and radio emission until first arrival of the isotropic component of particles of energy above 100 Mev is about 1/2 hr for flares in the western hemisphere and about 1-1/2 hr in the eastern hemisphere.

At a peak emission of 10^{-18} $w/meters^2$ cps (50 times normal) in the microwave region, the integrated intensity generally will exceed 10^8 $particles/cm^2$ sec. At about one third of this radio output, the particle flux generally will exceed 10^7 $particles/cm^2$ sec and may exceed 10^8 $particles/cm^2$ sec. When the microwave emission is less than about 2×10^{-19} $w/meter^2$ cps, the cosmic ray event is not likely to be a major one.

The low probability of a major flare coupled with the expectation of attaining at least 30 min warning by microwave monitoring on earth and transmission of the warning to the moon would apparently reduce the hazard to an acceptable level. The steps required to attain adequate protection consist of taking shelter beneath about 5 gms/cm^2 and taking antiradiation sickness medication.

This ability to make short-range forecasts is summarized in the following paragraph quoted from Solar Proton Manual (NASATR R-169):

> "Turning now to the characteristic intensity-time profiles of the solar cosmic rays as observed in the earth's vicinity, we see that the average initial delay from the time of the peak optical (and radio) emission until the first arrival of the isotropic component of solar particles at the earth (for particle energies above 100 Mev) is about 1/2 hr for flares in the western hemisphere and about 1-1/2 hr in the eastern. The average risk times for the particles with energies above 100 Mev are 2-3 hr and 6-8 hr for the western and eastern hemispheres respectively. The onset and rise times for the isotropic component of particles with energies above 30 Mev are longer by a factor of 2 in each event but otherwise show the same characteristics."

Based on data for solar cosmic ray outbursts from 1956 to 1961, the feasibility of attaining adequate protection is considerable. A shield of only 1 gm/cm^2, such as might be afforded by the space suit alone, would protect against all protons of less than 30-Mev energy. The fact that the flux tends to be omnidirectional is important in reducing the dosage at depth, and a careful computation should be carried out allowing for the $\frac{dE}{dx}$ as a function of energy and taking account of the fact that $\frac{dI}{dE}$ applies as E_{max}^{-4} (approx.). These estimates may indicate that it would be feasible to protect the more vital organs with specially designed shielding. Because of the information obtained from earth and orbiting satellites, no measurements on the lunar surface appear to be required during early exploratory missions.

e. Magnetically Trapped Radiation

Although no significant magnetic field has been detected on the moon, a weak magnetic field may be generated by interaction with solar plasma. A magnetic field could trap charged particles, such as solar protons, and cause Van Allen belts around the moon. Principal evidence against the existence of significant radiation belts around the moon includes the Russian lunar shot (Levantovskii, 1960) which did not detect a magnetic field with a magnetometer sensitive to about 60 gamma; neither was there any evidence of radiation belts.

In spite of the probably negligible value of the trapped radiation around the moon, it would seem desirable to make confirmatory measurements of the magnetic field and associated trapped radiation. Measurements of the magnetic field are considered in the chapter on solid-body geophysics. It would be desirable to monitor continuously for at least total dose rate in a tissue-equivalent detector,* not only during the entire flight (outside the scope of this report) but during the approach to the moon itself to detect local variations which might be ascribed to trapped radiation. Measurement of flux, energy and charge of particles is also desirable.

f. Primary Heavy Cosmic Rays

In addition to the protons and electrons constituting most of both the solar flares and the continuous flow of galactic cosmic rays, elements of atomic number to about 26 (iron) also occur. Their flux is now known to be low. Although the microscopic dose rate is very low, the ionization produced by these heavy cosmic ray particles is highly concentrated along the track of the particles, which makes the microscopic dose in tissue very high (thousands of rads in the track). Recent experiments indicate that even these highly ionized tracks cause very little effect in either the brain or the eye and presumably also in other vital organs. Although they may cause graying of spots of the hair, primary cosmic rays are believed not to pose a serious hazard for space flight (Curtis, 1962). Biological experiments to confirm these findings could be carried out in space.

Knowledge of the nature of cosmic ray activity is far from complete. Recent evidence may be summarized as follows:

- Solar protons predominantly in the energy range of 10 Mev to 100 Mev are received in most instances from great flares with Type IV bursts. (Type IV bursts consist of 200-mc/sec radiation which occurs after solar flares; they last an hour or so during which the intensity first grows then slowly subsides; unlike other types of solar radio emission, the

*A radiation detector can be made tissue-equivalent in at least two ways: (a) by using a low-Z detector material whose dose rate under a given flux is similar to that of tissue; or (b) by surrounding the detector with an equilibrium thickness of tissue-equivalent wall material, such as polyethylene, in accordance with the Bragg-Gray principle.

intensity exhibits no rapid variation with time. Type IV bursts were present in all recorded cases where cosmic rays reach the earth.)

- Delay in arrival time for protons reaching the earth substantially exceeds any possible straight-line trajectory from sun to earth for particles of such energy.
- A high intensity of solar protons is more probable if the event occurs during a Forbush* decrease rather than at any other time.
- The flux of solar protons probably will increase if, during the event, there is an onset of a Forbush decrease.
- During a Forbush event, the magnetic field in space becomes great enough to partially exclude cosmic radiation; a flux of about 10^{-4} gauss is estimated to be adequate to do this. The fluxes measured in space by Pioneer V exceeded this limit by about a fivefold margin.
- A Forbush event in space is accompanied by a sudden change in magnetic field.
- The Forbush event is not a geocentric phenomenon. A Forbush event is probably due to magnetic fields associated with an earlier solar event. The plasma carrying its magnetic field balloons from the site of the solar flare; the magnetic lines return to the sun, and the solar protons tend to be trapped in this field. Near the solar surface, the proton injection results from switching effects due to time variations of the field rather than from diffusion.

The need for cosmic ray and magnetometer stations in space is obvious since there is clearly a need to correlate observations near the earth with those elsewhere in space. However, there is no compelling reason to prefer stations on the moon rather than in a satellite in a lunar orbit.

No magnetic field was detected on the Russian lunar fly-past. The field at the earth will be 10^{-6} of that 1400 miles above the lunar equator. Thus, one would not expect to detect a modest lunar field at the earth's surface. Any field of the moon would probably be more or less along the direction of the rotation axis. Thus, the superposition of earth and lunar field could only be expected to show earth diurnal fluctuations with a superimposed lunar-month modulation; i.e., the modulation would be at a period

*A Forbush event is a sudden decrease in flux of cosmic rays which have originated beyond the solar system.

of about 1-1/28 earth days. Unless the moon has a magnetic field or an anomalous permeability, it could not exert any influence on the solar proton flux except to the extent that it distorts plasma with associated field--generally the dimensions of plasma bubbles are large compared to lunar dimensions and possibly also large compared to earth-moon radius. Thus, from this consideration there appears to be no reason to prefer a lunar station over any other location in space. A cosmic ray station would be of little value unless accompanied by a magnetometer station.

Differences between flux in space and flux of heavy primary cosmic rays which strike the moon would seem to depend primarily upon the intensity of the magnetic activity on the moon and the orientation of the surface. One advantage for measuring cosmic rays on the moon rather than on an orbiting or free-flying vehicle is that the moon, if it has no magnetic field itself, presumably would be more stable in the space magnetosphere and thus might give truer measurements. The presence of heavy cosmic rays can be detected if the particle spectrometer is used.

It would be desirable to expose nuclear emulsions on the lunar surface during the landing because of the simplicity of the instrument and the potentially useful data that could be obtained.

g. Lunar Radioactivity

The moon's natural (geological) radioactivity probably constitutes as low a biological hazard as does the earth's. Local variations in natural radioactive materials such as uranium, radium, polonium, and potassium are presumably as possible as they are on earth, but they would not be expected to produce significantly larger concentrations or more hazardous intensities of radiation on the moon than on the earth. Because of their ease and possible importance, however, confirmatory measurements of total ionizing radiation (dose rate) emanating from the moon's surface are desirable for reasons of hazard assessment.

Measurement of geologically residual radioactivity would have considerable value in determining the origin and history of the moon. Such measurements are considered earlier in Section F of the chapter.

Radioactivity of the lunar surface induced by solar protons, alpha rays, and neutrons has not been measured. However, the induced activity must be so low as to represent a negligible direct radiation hazard. Most of the energy of the incident radiation is expended in nonnuclear interactions such as ionization; low-energy (a few kilovolts) charged particles such as the protons of the solar wind do not have energy enough to induce radioactivity, and most of the elements likely to be present in significant amounts on the moon's surface (aluminum, silicon, etc.) do not form radioactive isotopes by proton bombardment at modest energy.

The credible upper range of radioactivity can be estimated by taking the high-energy proton flux impinging on the moon's surface during the worst flare, choosing a likely element with a high possibility of hazard and computing the maximum radioactivity which could result if the surface were 100 per cent of the most favorable isotope of that element. A rough estimate has been made, using the reaction Fe^{58} (p, n) Co^{58} and the July 1959 solar event, assuming one-third of the protons induced a reaction with a cross-section of two barns. The estimated dose rate at the moon's surface (less than 1 mR/hr) would be measurable, but the hazard would be negligible. Thus, there is no compelling reason to measure radiation from induced radioactivity on the moon's surface merely to assess the hazard. Nevertheless, if any radiation-measuring instrument is available, it could make some measurement of surface radioactivity simply, and, therefore, it is only prudent to do so. On the assumptions of simplicity and availability of an instrument (such as the survey dose rate meter) for other purposes, this measurement would be useful. Because there is no atmosphere on the moon, it is feasible to measure the radioactivity of the surface from an orbiting satellite, as the dose rate is independent of height above the surface. This would permit detection of any diurnal effects on the lunar surface.

The possibility should be considered that proton or neutron bombardment of materials in the lunar crust would create enough deuterium or radioactive tritium to make impotable any water recovered from the lunar surface. Calculations of credibility should be made, based on known proton fluxes. Samples of lunar material returned to earth should be analyzed for light hydrogen, deuterium and tritium. No measurements of these isotopes during the lunar landing itself are recommended because of their complexity.

h. Secondary Radiation

Secondary radiation may emanate from the lunar surface in the form of backscattered primary radiation (protons, alpha rays, elements of higher atomic number, electrons, and photons), as well as bremsstrahlung, photoemission electrons, neutrons, mesons, or sputtered atoms resulting from bombardment of the moon's surface by the primary radiation. The intensity and energy of the secondary radiation must be less than that of the primary. Even if the reflected radiation were equal to the incident, the dose rate would only be doubled and would still be small. Measurement of secondary radiation on the lunar surface in connection with hazard assessment, therefore, seems of minor importance. (Reflected radiation can be at least partly detected with measurement of surface radioactivity.)

i. Radiation During the Lunar Night

All the preceding discussions relate to radiation during both lunar day and night. During lunar night, the particulate radiation of both galactic and solar flare (if present) origin is expected to be comparable to radiation during the lunar day, because the radiation is almost isotropic. The solar wind, however, appears not to be isotropic (Snyder, 1962) and, as mentioned earlier, would be interesting to measure on the moon at night.

3. Indirect Radiation and Associated Hazards

a. Sputtered Surfaces

Radiation of the type striking the lunar surface can sputter off, vaporize or chemically or physically deteriorate (sometimes selectively in the hard vacuum) very thin surface coatings of space suits, equipment and the like. However, the low flux of particulate radiation hitting the moon's surface, which would produce a maximum of a few rads of all combined ionizing radiation, is too low to produce such effects in a few hours or days. It is estimated (Reiffel, 1960) that a few hundred angstroms of a surface might be sputtered off in a few weeks.

Ionizing radiation also can affect materials such as equipment and instruments. At a few-rad level during a few-day lunar mission, however, no problem is foreseen. Radiation-induced transient effects in instrumental circuit behavior must be considered in terms of the effects on specific instruments, but such effects are expected to be small on the instruments applicable to the measurement of radiation.

b. Chemical Reactivity of the Lunar Surface

There is a possibility that the lunar surface might be chemically reactive. Solar particle bombardment combined with the ultrahigh vacuum and high-surface temperatures during the lunar day would tend to cause molecular degradation of lunar materials such as silicates. If oxygen were knocked out of a silicate molecule with sufficient energy to escape from the molecule (and possibly from the moon), the remaining less volatile silicon and metallic elements -- such as iron, aluminum and calcium -- could be left in a highly reactive state. Particulate bombardment might also cause solid dislocations or unusual ionic states or produce free radicals. These higher-energy states could release their energy on contact with foreign surfaces.

Conceivably, such a reactive powder might damage the astronaut's shoes, space suit or equipment in two ways. First, the powder might react directly with organic materials in the shoes, suit and equipment, causing corrosive and/or thermal degradation. Second, a thin layer of reactive dust, possibly with electrostatic attraction for an oppositely charged astronaut, equipment or vehicle, might cling to its surface. This dust then might react with oxygen or moisture during the return to earth, generating heat which could damage the surface material.

The possibility of the first type of damage (direct reaction) seems remote, because the limited degree of contact between two solids generally limits the rate of solid-solid reactions at moderate temperatures. Under static conditions a thin film of reaction product would form, and the reaction then probably would cease. However, the motion of an astronaut's shoe in contact with a reactive lunar surface would tend to favor continued reaction, because abrasion might be sufficient to remove the protective layer of reaction product. Reactions which might occur include the abstraction of halides from, and increased cross-linking of, organic polymers, both of which would degrade the polymers' structural properties.

It is difficult to predict the likelihood of solid-state reactions under the conditions of the lunar landing, but experiments could be conducted on earth prior to the lunar mission to determine the reactivity of proposed suit and equipment materials with finely powdered alkali, alkaline earth and transition metals in high vacuo and at the maximum expected lunar surface temperature. Furthermore, because of the possible disastrous effects of even a small pinhole in a space suit and of the nuisance value, if not worse, of the dust reacting with surfaces of instruments, etc., it would seem prudent to develop a simple chemical reactivity test that could be made before debarking from the Lunar Excursion Module. Perhaps the simplest test would be to drop samples of materials expected to contact the lunar surface and observe from the LEM any change in appearance or in temperature as revealed by a temperature-sensitive paint or by a thermocouple with leads to the LEM. The thermal criterion for reactivity is probably sufficient, for most corrosive reactions will be exothermic, and heat losses from the test piece will be slow, due to the lack of convection and the low thermal conductivity of the lunar surface.

The second type of damage, caused by heat release during subsequent exposure of an adherent layer of the dust to oxygen or water vapor, is somewhat easier to assess. For an adherent layer of finely divided calcium powder, equivalent to a 1-mil thickness of the solid metal, oxidation would release 15 cal per cm^2. If all the heat were generated quickly and absorbed in the calcium oxide formed, a temperature of several thousand degrees would be attained. A more realistic estimate of temperature is based on the assumption that all the heat is absorbed by a space suit of 2 gm/cm^2 density and 0.3 cal/gm deg specific heat. In this case, the temperature would rise 25°C. Temperature rise is clearly a function of the rates of oxidation and heat transfer in a real situation and is best determined in advance of the mission by experimental test if it is considered possible that any dust would be allowed to re-enter the LEM with the astronaut.

An experimental study of the degradation of probable lunar materials in a simulated lunar environment of proton bombardment and high vacuum could indicate the likelihood of reactive materials being encountered on the lunar surface. It would also seem prudent, however, in the course of developing a space suit and other equipment, to aim for chemical inertness and to test materials of construction for reactivity in the dry state and in high vacuum with elemental materials of the type which might be expected to occur on the moon's surface.

Testing lunar dust reactivity from the LEM is worth considering, because it requires so little effort, power and weight. If it is evident that a reactive (and probably pyrophoric) dust is adhering in considerable thickness (sufficient to cause ignition to space suits, equipment and vehicles), consideration should be given on the return trip to earth to exposing the surfaces to moisture or oxygen at a slow rate to minimize temperature rise.

4. Measurement of Radiation-Produced Phenomena

Lunar fluorescence and albedo and the low thermal conductivity of the moon are phenomena related to exogenic radiation striking the lunar surface. None of these produced phenomena constitute a problem to astronaut safety, but are measurements that might be performed on the moon to contribute to an understanding of the origin and history of the moon and to data that could be applied to point extrapolation from known areas to unexplored regions.

a. Moon Fluorescence

It has been estimated (Baldwin, 1963) that as much as 10 per cent of the light of a full moon might be the result of fluorescence of the lunar surface. The exciting radiation probably would be mostly ultraviolet light from the sun. Information regarding the extent of fluorescence could be obtained advantageously by measurement during a landing. A simple light meter suitably filtered and collimated to measure only visible light coming from the moon's surface could be alternately exposed to the full intensity of the sun's light and then to the same light filtered to remove the ultraviolet and low energy corpuscular radiation but passing essentially all the visible light. This measurement would have to be made during a lunar day. Alternatively, an ultraviolet light source and light meter, filtered to measure only visible fluorescence, could be employed during lunar night. Similar measurements could be made on samples of lunar surface materials returned to earth. Provision should be made to retain any samples in a vacuum-tight container so their properties, such as fluorescence, conductivity, etc., can be measured on earth before exposure to the atmosphere.

b. Lunar Albedo

Among the factors postulated to contribute to the generally low albedo of the full moon's surface (7 per cent) are crystalline disorder, opacity and high porosity (Baldwin, 1963). These three conditions could be produced by radiation (as well as by other factors). Crystalline disorder can be produced by radiation, especially by particulate (or corpuscular) such as protons, helium, heavier nuclei, and neutrons. An F-center type of crystalline disorder induced by knock-on collisions of particulate radiation displacing atoms of the crystal can cause a darkening of color and an increase in opacity. Opacity also would be increased if free conductive metal atoms such as iron and calcium were produced by the radiation decomposition of lunar clays and volcanic ash. Porosity could be the result of millions of years of radiation sputtering action in which particulate radiation caused atoms at the moon's surface to be ejected. The ejected atoms might escape the moon or, depending on their velocity, atomic weight and volatility fall back to the surface in a loosely packed porous structure.

The most important measurements related to lunar albedo to be made on the moon's surface are to verify porosity, color and opacity of the surface material by nonradiological methods. A measure of time-integrated particle flux on the lunar surface to confirm the values already known for solar space also would be desirable.

c. Low Thermal Conductivity

The moon's low thermal conductivity is believed to be at least partly explainable by a high lunar porosity. Surface porosity could be the result of not only ejecta from micrometeoroid impacts followed by cold welding in the high vacuum of the moon but also of radiation-induced atomic sputtering. Measurements during the lunar day and night of the proton and other heavy particle flux deserve to be made if other considerations of magnetic fields, lunar charge, evidence of micrometeoroid impact phenomena, etc., indicate the need for such radiological data to explain the porosity of the moon's surface.

5. Radiological Measurements, Observations and Experiments

The study group considered 17 pertinent radiological measurements and experiments. These are shown in Appendix C. They were rated on the basis of their contributions and importance to determining hazards, trafficability and basing problems, and to the origin, history and age of the lunar surface and earth-moon system. Some were eliminated because of negligible contributions to solution of fundamental lunar problems and others because they could be performed as well or better with earth or lunar orbiting satellites. The radiologic experiments and measurements selected for early APOLLO missions are:

- Particulate radiation flux
- Chemical reactivity of the lunar surface
- Integral radiative dose
- Total ionizing dose
- Cosmic ray flux (with magnetometer)
- Electron density

6. Importance of Selected Radiological Measurements

a. Hazards

Radiological measurements will be of major significance to insure astronaut safety. Possible radiological hazards already have been discussed so are only summarized here. The principal radiological hazard of a lunar landing appears to be the direct biological hazard to man or instruments from infrequent major solar flares. Prediction of safe periods for a mission and earth-based observations and warning to lunar astronauts is recommended as preferable to similar observations on the moon itself. With the exception of flares, it appears highly probable that there will be no radiological problem to astronauts during a lunar landing because the overall radiation level is low. However, precautionary and/or confirmatory measurements of the integral radiative dose and total ionizing dose should be made immediately upon landing and periodically thereafter. Any measurements of radiation intensity or type needed for radiological safety probably can be made just as well from a satellite orbiting the earth or moon, with the possible exception of measurements of any Van Allen belt-type radiation around the moon. The existence of such belts appear to be improbable but, should they exist in strength, could be a significant radiation hazard.

It seems prudent to consider radiation measurements and instruments. During the landing these at least could give first approximation of the total radiation capable of being absorbed by the astronaut. The ideal instruments should yield as much other specific information as possible regarding the radiation type, energy, flux, and directionality with a minimum of weight and complexity. The priority for a multipurpose instrument is considered higher than for one measuring any single radiation type. This priority increases with the increasing simplicity and lightness of the instrument. For example, a simple pocket ionization chamber of a type suitable for a lunar mission would seem to merit a high priority.

The lunar surface might be chemically reactive due to the effects of particulate radiation in the high temperature ultravacuum lunar environment. Reactive and phyrophoric dusts might damage the astronaut's shoes, space suit or equipment either by solid-state reactions or by thermal degradation. Tests must be made to determine if reactive dusts and rock surfaces exist on the moon. Sputtering produced by particulate radiation might cause surface coatings of equipment to be sputtered off, vaporized or chemically and physically deteriorated.

In addition to direct and indirect radiological hazards, the following deleterious conditions may be induced by radiation:

- Radiation-enhanced vomiting tendencies. Vomiting is recognized to be a potential biological problem for an astronaut in a space suit in zero or low gravity. Radiation in massive doses (over 50-100 rads) is known to induce nausea and vomiting in many people. The extent to which weightlessness and other abnormal environmental factors would affect the point at which radiation induces nausea is not known. Medical opinion should be sought on this point. It seems improbable, however, that the low level or radiation (probably less than 10 rads for a few-day lunar mission within no major flare) would be high enough to be an important factor.

- Radiation effects on visual acuity. The absence of an atmosphere will produce sharply defined light and dark areas on the lunar surface. The vision of an astronaut may be affected when his eye is suddenly exposed to the brightness in sunlight areas or when he accidentally looks into the sun. Because his eyes may be completely dark-adapted, the slowness of pupil reaction while fully dilated may result in a maximum dosage of light reaching the inner eye and retina. Although the blink reflex is about 1/10 sec, sufficient deterioration in visual acuity may occur so that some time may elapse before full vision is restored. In addition, the possibility of retinal burns should be considered.
- Radiation-produced ozone. The effect of radiation in producing toxic ozone in the oxygen of the astronaut's breathing oxygen tank might also be mentioned. G-values for the production of ozone in liquid or gaseous oxygen average about 10 molecules of O_3 formed per 100 electron volts of ionizing radiation absorbed by the oxygen (Riley, 1962). A dose of 10 rads (6×10^{14} ev/gm) thus would create about 10^{14} molecules of ozone per gram of liquid oxygen or about 0.003 ppm. The natural instability of ozone will reduce this concentration. The threshold limit for ozone in air, under which nearly all workers may be repeatedly exposed day after day without adverse effect, is about 1/10 of a ppm (adopted at the 23rd annual meeting of the American Conference of Governmental-Industrial Hygienists, Detroit, Mich., Apr. 9 - 12, 1961). Thus, the ozone produced by radiation is not expected to cause a problem.
- Electrostatic effects. Radiation-induced electric charges in loose surface materials may seriously impair radio communications between the astronaut and LEM. Similar effects have been observed in tracked vehicles operating in desert areas. Therefore, it may be of interest to measure the charges on particles and their distribution and electron density.

b. Basing

Shielding requirements for personnel and equipment depend on knowing the total radiation dose and especially the radiological flux during major solar flares. Base construction may need to be timed for intervals when flares are at low intensity.

The presence of reactive dusts and rock surfaces would present a serious problem to lunar construction and basing because of potential effects on men and equipment. Development of base design and construction concepts is contingent on the extent to which lunar materials are reactive.

c. Origin, History and Age of Lunar Surface

Solar winds, solar flares and primary heavy cosmic rays may cause sputtering of rock surfaces and hence act as active agents of erosion and transportation. Darkening of rock surfaces may be caused by exogenic ultraviolet ray emanations, and solar X-rays also may produce surface modifications. Hence, the origin and history of the lunar surface can be interpreted by understanding the nature of these forces and their effects on lunar material.

7. Nature of Properties Measured

All the radiological measurements discussed in this section will be made in place; none will necessitate sample return to earth. Electron-density and cosmic ray experiments will continue after departure from the moon, and data will be telemetered to earth. All the proposed measurements and experiments will be taken over a time period and, with the exception of the electron-density measurements, will require multiple readings. With the exception of the passive intergrated radiation-dose measurement, the radiological experiments are active measurements. The nature of the selected measurements and experiments is summarized in Appendix C.

8. Radiological Equipment and Instrumentation

Equipment and instrumentation (discussed in detail in Chapter V) required for the radiological observations and experiments are:

- Integrating personal dosimeter
- Particle survey dose rate meter
- Particle spectrometer
- Chemical reactivity detector
- Magnetometer (for cosmic ray flux)
- Electron density sensor

a. Integrating Personal Dosimeter

Film badges worn inside the space suit, with shielding to cover ranges, could be used. The exposed film would be developed on earth. Consideration also should be given to adapting existing models of Lauritsen electroscopes for this purpose. They would have to be modified to the desired dose ranges of 1-30R and 1-1000R and designed for the lunar environment.

b. Portable Survey Dose Rate Meter

The survey meter successfully flown on the Mariner II probe to Venus and described by Hoffman (1962) could be modified to meet APOLLO needs. Because the output of this instrument is primarily digital, a visible rate meter should be added.

Rowland (1964) described a portable survey meter which could be used to measure dose rate. It uses a scintillator and a multiplier phototube, and a rate output is provided in addition to a means for interrogating the scalar memory built into the instrument.

c. Particle Spectrometer

There are several types of particle spectrometers which can be modified for use on APOLLO missions. All of these instruments (Fisher et al., 1963; Van Allen, 1963; Simpson, 1964) have digital output and would have to be altered to meet mission requirements. The instrument should be designed so it can be left on the lunar surface to take measurements for a time sufficient for one lunation and if possible for a major solar flare. Cumbersome shielding may be required to permit recording of high energy solar flares.

d. Chemical Reactivity Detector

This instrument will have to be developed but all that is required is a simple device to indicate the reactivity of lunar surface material to the space suit and equipment. A probe instrumented with thermocouples or temperature-sensitive paint, covered with samples of space-suit material as well as inactive material for comparison would suffice. This could be lowered to the lunar surface to take temperature measurements and be withdrawn for inspection through the port of the LEM.

e. Magnetometer

A low field helium magnetometer included in the solid-body geophysical equipment can be used to augment cosmic ray measurements. Bursts of radiation will cause a change in the lunar electrical field and, as a consequence, alter the magnetic field. Changes in the magnetic field will indicate the nature and intensity of the cosmic radiation. Existing models of magnetometers can be adapted easily for lunar use.

f. Electron Density Sensor

This instrument will require development. The design concept for an instrument to measure electron density within a small volume is a difficult one, as the electron density at the lunar surface changes substantially over a short distance and its order of magnitude cannot be reliably forecast. The required type of instrument might depend upon the change in dielectric constant of the vacuum due to the presence of free electrons and take the form of an open-structured resonant cavity. The problem with such instrumentation is operation during the lunar day; the anticipated problems are those of dimensional stability and anomalous behavior due to secondary emission.

An alternative type of instrument could consist of a resonant system such as a shorted lecher wire system with a static magnetic field normal to the electric vector; the frequency and magnetic field would be chosen so that free electrons precess at their cyclotron frequency. A signal with electric vector normal to the steady magnetic field and to the electric vector of the lecher wire system then should be emitted with an intensity proportional to the electron density. The major problem here is again the requirement for performance during the lunar day, since such an instrument tends to require laboratory conditions for satisfactory performance.

9. Ranking of Radiological Observations and Measurements

The radiological observations and measurements selected for early APOLLO missions were ranked on the basis of their importance to the fundamental problem areas inherent in lunar exploration. Most important is the determination of particulate radiation flux and the chemical reactivity of the lunar surface. The total ionizing dose and integral radiative dose are next in importance and could be critical factors in mission success. Measurements to determine cosmic ray flux and electron density are the remaining two experiments recommended.

Data obtained from the radiological determinations are crucial to astronaut safety and to engineering concepts for lunar basing and also will yield considerable information on the origin and history of the lunar surface.

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CHAPTER II

GEOPHYSICS

A. SUMMARY

Lunar geophysics is the application of the methods and instruments of physics to obtain information about the solid moon, especially structures and phenomena not visible or detectable on the surface. Those branches of lunar geophysics related to atmospheric geophysics on earth are discussed in Chapter I. The methods studied for use in lunar geophysics are gravitational, thermal, seismic, and magnetic-electrical. Their evaluation for use in lunar exploration depends on understanding (1) the basic physical principles involved, as these affect their successful utilization; (2) the specific contribution of each type of spatial and time series data to be obtained for solving lunar hazards, logistics and scientific problems and (3) operational and instrumental problems caused by lunar environmental and logistic constraints. All of these factors have been considered in deriving diagnostic criteria to select the best geophysical techniques and instruments to use -- both individually and in combination.

Available geophysical instruments for terrestrial surveys require extensive modifications before they can be expected to obtain useful lunar data. (Efforts, however, have been made to design or construct a number for lunar operations.) Appendix D tabulates results of a comprehensive survey of all pertinent instrument characteristics. Based on this phase of the study, one to three instruments for each major geophysical survey method were selected as possible candidates for the APOLLO mission and estimates made of time required to build them. A detailed engineering evaluation of their pertinent characteristics was made. These are included in both the computer evaluation analysis and the more subjectively derived priorities for the Scientific Instrumentation Package (SIP) and mission plans. They are discussed in detail in Chapters V and VI. Because of severe time, mobility and logistic constraints in the early missions, emphasis must be on single-location readings and limited time series observations near the LEM landing site rather than on more conventional areal surveys. Such surveys should be conducted during later missions when stay times are extended and astronaut mobility is improved. The SIP, therefore, must be depended upon heavily for additional data. This has been considered in selecting the instrumentation for it as well as in defining the sequential data gathering and telemetry design.

Instruments for geophysics include a lunar tide meter, absolute gravity meters, a seismometer package for monitoring both noise and moonquakes, a total field magnetometer, and an instrument for measuring susceptibility in place. Also recommended are two wire loops about 100-ft long, to be arranged mutually perpendicular to one another, with their associated electrodes. These are to be used in combination with the magnetometer to make lunar field measurements and to study magnetohydrodynamic waves. Alternative to the total field magnetometer and wire loops, a 3-component magnetometer could be used.

Use of more conventional electrical methods has not been emphasized for initial missions because of the liklihood of poor electrical contact due to the absence of moisture in near-surface material and the more limited application of their results to the solution of lunar problems. Instrument weight, power and volume requirements and time required for measurements also influenced the decision not to emphasize electrical methods on early missions. Active types of seismic measurements have been deleted as well for similar reasons and because of the hazard explosives represent to the astronaut. Recommended instruments for thermal measurements include a heat flow meter for surface flow temperature measurements as well as appropriate temperature measuring devices to be installed in the astronaut's boot and the LEM landing gear. Both a thermocouple loop and platinum resistance loops have been considered for the surface temperature measuring instruments.

1. Measurements

Gravity measurements will consist of observations of the acceleration of gravity on the lunar surface. The results can be applied to solution of problems involving elasticity, subsurface density and structure, and eventually the shape of the moon. Priorities for widespread seismic, gravity and magnetic measurements in early missions will not be high since these bear little relation to hazards or trafficability, and stay time and mobility are limited. Because of the previously described active mode limitations, early seismic measurement emphasis will be on detecting moonquakes and other effects of lunar structural stresses using the passive mode. Magnetic experiments will be limited to measuring a few changes in the total magnetic field in time and space. The same applies to electrical measurements which will be confined to limited lunaric current studies in combination with magnetometer measurements that also can be used for gathering magnetic data. Thermal measurements proposed are temperature, thermal conductivity, heat flux, thermal diffusivity, and thermal emittance. Initially the measurements will be concerned primarily with astronaut hazards and lunar basing technology rather than solution of scientific problems, again because of time and logistic constraints. In addition, comprehensive measurements should be made on samples returned to earth for, as examples, magnetic susceptibility, thermal and electrical conductivity, resistivity, density and acoustic velocity properties. Subsequently, these results can be incorporated with lunar field measurements to augment their application in the solution of lunar problems.

Radioactivity and micrometeroid flux measurements, because of the importance of these factors in modifying lunar surface features and materials, are discussed in Chapter I (Geology and Selected Geophysical Processes).

2. Conclusions

One facet of the overall problem should be stressed -- the need to learn prior to the APOLLO missions as much as possible about geophysical measurements under possible lunar environmental conditions by means of earth-based experiments. Results would be valuable in recommending optimum types of instruments to be used to achieve various mission objectives. Also, geophysical data obtained within the next few years by unmanned lunar missions will increase understanding of the composition, structure, origin, and history of the moon, and these results should be used to make the necessary modifications. However, how much useful information is obtained to interpret these data correctly depends largely upon the ability to determine early in the lunar exploration program the origin of specific features of the moon surface, e.g., volcanic versus meteoroid origin of major surface structures. To develop this ability, geophysical properties of terrestrial features of similar origin must first be determined and cataloged. In short, pertinent terrestrial phenomena must be understood before an effective analysis of empirically derived geophysical lunar data can be made.

B. GRAVITY

1. Definition and Scope

Gravity measurements on the moon will consist of observations of the acceleration of gravity on its surface. The observed acceleration will change from place to place and from time to time, and the existence and magnitude of these changes will be evidence of physical facts about the moon. The scope of gravity measurements will be as wide as logistics allow. Observations at a single location, at two neighboring locations, at intervals along a short or long traverse, over a small or large area or over a moonwide network will all be useful in solving problems of lunar structure and the figure of the moon. Single-location readings should also be taken in a time sequence at each landing site and at other selected locations when surface transportation becomes practical.

2. Basic Physical Principles

Basic physical principles involved in gravity measurements and in deducing information from them are the gravitational attraction between masses as given by Newton's Law, the centrifugal force due to motion in a curved trajectory and the tendency of materials to resist deformation under stress.

a. Law of Gravitation

The main cause of gravitational acceleration on the moon's surface is, of course, the moon's mass. The observed acceleration changes with the distance from the center of that mass -- i.e., due to changes in elevation and to the ellipticity of the moon's figure -- and with horizontal position due to the presence of local or large-scale selenological structure. A secondary cause of such acceleration is the presence of the earth and sun, which causes changes in the observed gravity as their distance and relative directions vary.

b. Centrifugal Force

The moon and the earth revolve about a common center of gravity, and the moon revolves about its own axis. Each point on its surface is thus subject to a centrifugal force which changes with the angular velocity of that point. The motion of the moon with respect to the sun produces similar though much smaller forces. These forces are usually computed as part of the so-called tide-producing force; at any rate, they affect the observed gravity. Their effect is readily computable and thus is subtracted from the observations.

c. Elasticity

The tide-producing force, the sum of the attraction of the sun and moon and of the orbital and rotational centrifugal forces, produces a stress in the moon's body which tends to deform it. On earth, this stress causes a change in the local ocean level and, in addition, a strain in the earth's body which is a measure of its rigidity. On the moon, there are no ocean tides, but it is anticipated that the moon's body will yield to the tide-forming stresses, by an amount perceptible with the ordinary gravity meter, due to the change in elevation or distance from the moon's center.

3. Types of Phenomena To Be Measured

a. Single-Point Observations

1) Absolute Value

The first observation of gravity will be the measurement of its absolute value at the landing site. This value will serve as lunar gravity base No. 1 and will provide, as soon as the true elevation of the base is known, a first direct measurement of the moon's density, now known only from astronomical data. In the interest of the long-term study of the moon, gravity bases should be established wherever other measurements are made. As the number of these bases increases and other data combine with their gravity values, more and more knowledge of the moon's figure and structure will come to light.

Useful in the beginning would be a reading accurate to ± 5 milligals. As more bases are established, an accuracy of ± 0.5 milligal should be sought.

2) Gradients

The second single-point observation of gravity should be observance of the horizontal and vertical gradients of gravity on the moon's surface. This gradient, when separated from the gradients due to local effects, will furnish an approximate value for the moon's ellipticity -- just as the north-south gradient on earth, commonly known as the latitude correction, gives a first approximation of the earth's ellipticity or polar flattening. The gradients should be measured to ± 1 Eötvos or 10^{-6} milligals/cm.

3) Tides

The third single-point lunar gravity observation should be designed to record changes in the local value of gravity due to the tide-producing forces and to the yielding of the moon's body to these forces. The same phenomenon is observed on earth; the change in tidal forces during the day is about 0.25 milligal, varying of course with relative apparent positions of the moon and sun. The change, for any location and time, can be computed with fair accuracy, and is what would be observed if the earth were perfectly rigid. It has been found, however, that the observed changes are greater than the calculated change by about 20 per cent. The excess is attributed to the yielding of the earth to the change in force, and the amount of yield--about 1 ft--is a measure of the earth's rigidity.

On the moon, the difference in tide-producing force is about 1 milligal. If the moon had no rigidity--i.e., if it behaved like a liquid--this change in tide-producing force would produce a maximum yielding, dependent on the location, of some 16 meters (Urey, 1959) which would, in turn, cause a decrease of some 3 milligals in the acceleration (see Report, Contract No. NASw-581, 1963). The observed change in local gravity thus will be between 1 and 4 milligals, and its value can be used to compute a first approximation to the rigidity of the moon's body. A completely yielding moon would show tides of 16 meters and a completely rigid moon would not yield at all. The yielding will be some number in this range and may cause fracturing and other surface effects important to both geology and engineering.

The main lunar tidal cycle is, of course, about one lunar day long, which means about a terrestrial month. Accordingly, measurements to be significant should be made at least every 12 hr or so with an accuracy of 0.1 milligal.

b. Gravity Surveys

Gravity surveys are useful in obtaining information not available from surface geology about the roots of visible structures, and in deducing the existence and nature of geologic structures not apparent on the surface. They are used extensively for this purpose on the earth and are expected to be even more useful in the same way on the moon because of the probable lack of a systematic and areally extensive stratigraphic sequence--which is so powerful an aid in deducing terrestrial subsurface information. On the moon as well as the earth, structure of any sort is usually associated with a change in the density of the material involved. For this reason, the gravity meter and the gradiometer will be essential to any systematic study of the lunar subsurface.

Gravity surveys can be conducted on small or local, medium or regional, large or continental scales, depending on depth and extent of the target feature. Surveys with a specific target should extend well beyond its horizontal extent to provide suitable background information for establishing regional gravity so the anomaly may be properly defined. For the same reason, surveys also should cover an area whose diameter is at least five times the depth of the target structure. It follows that gravity surveys (for the first few lunar missions) will deal with local features only because of limited surface mobility. Later, when manned and unmanned roving vehicles can make more extensive exploratory trips, longer and larger features can be explored.

The importance of gravity surveys is such that they should be carried out routinely by any astronaut moving on the moon's surface. The instruments can be operated rapidly and are easy to read, lightweight and convenient to carry. If elevations are to be measured as part of the astronaut's mission, the gravity meter should be carried and read at each station; if no elevations are to be recorded, the gradiometer should be used.

1) Local Gravity Surveys

Local gravity surveys will be the key to subsurface geologic structure. Measurements will be obtained of the density of the material in topographic features and lateral changes detected in surface density due to voids or honeycomb structure; this may be important in engineering and construction. The surveys also will give evidence of subsurface faulting or doming. They will detect subsurface masses that are heavier (such as basaltic intrusions or ore masses) or lighter (such as possible masses of ice) than the surrounding material. They will provide a means of differentiating between small-scale craters caused by meteoric impact and those caused by volcanism. Finally, and perhaps most important, lunar missions will undoubtedly discover geologic features that have no obvious terrestrial counterparts and may, therefore, be most productive of new knowledge about the moon and its history. Gravity probably will be the key to information concerning such unanticipated structures that cannot be deduced from surface data.

Local gravity surveys will be the most important geophysical method for solving subsurface problems on the moon, for several reasons. The seismic method, easily the most important terrestrial subsurface tool, depends largely for its usefulness on the quality of layering of stratified materials or sediments. Whatever stratification exists on the moon, its physical properties are unlikely to be closely analogous to terrestrial stratigraphy and less amenable to description by reflection seismology. In addition, required equipment is heavier and more elaborate than that required for gravity surveys and the energy source--largely explosives--is hazardous. For these reasons, seismology will be far less useful on the moon that on earth. Magnetic exploration may be difficult because of the probably weak lunar magnetic field; as are electrical methods because of the lack of moisture and consequent high resistivity. It follows that gravity will be by far the most important tool of the subsurface selenologist.

The scope or extent of local gravity surveys will be determined at first by the distance the astronaut travels on his exploratory mission. When specific targets for geophysical exploration are set, the extent of each traverse will, of course, be determined by its purpose. This may range from a few hundred feet to several miles. The accuracy of measurement required is of the order of 0.1 milligal or 1 Eötvos; this requirement will be less stringent in rough terrain or when elevations are only roughly measured. Other factors involved in gravity surveying requirements are discussed in detail in the section on surveying (Chapter IV, Section C).

2) Regional Gravity Surveys

In terrestrial exploration, these surveys are used to study such large-scale features as sedimentary basins and mountain ranges. They are useful in determining the thickness of sediments, patterns of faulting around basin edges, depth of mountain roots, extent of isostatic compensation, etc. Analogous features on the moon would be mountain ranges, medium-to-large craters, scar valleys, rays, circular plateaus, crater chains, domes, etc. If these features, as defined from telescopic observations to date, actually form types or genera of geologic structure, it is likely that their gravity anomalies will have diagnostic aspects which will contribute to the knowledge of their origin and their subsurface shape.

Regional gravity surveys will, of course, become possible only when lunar surface mobility is greatly increased. Their accuracy needs to be of the order of ± 1 milligal or 5 Eötvos.

3) Selenodetic Gravity Measurements

These measurements are analogous to geodetic gravity measurements on earth and will need to be made on a continental or moonwide scale. Selenodetic data will be obtained, of course, from local surveys--these data include the absolute magnitude of gravity and the magnitude and direction of the horizontal gradient of gravity. These data will be a clue to the local undulation of the selenoid and to the local deflection of the vertical. As astronauts acquire more freedom to move about on the moon's surface, better determinations of the gradient can be made and, as the surface is more fully covered with observations, the ellipticity or figure of the moon can be more and more closely approximated. (The deductions will be confirmed or refuted when lunar tracking stations for tracking lunar orbiting satellites are established.) Eventually, a selenodetic network comparable to the geodetic network now being built on earth will be established.

A secondary selenodetic problem is the difference in the substructure of the maria and terrae. It has been suggested that such differences exist, although they are probably not analogous to the difference between terrestrial continental and ocean substructure because no evidence as yet points conclusively (Baldwin, 1963) to the existence of a yielding mantle or of isostatic compensation in the moon. However, if there are differences, the principal key to their discovery will be gravity observations. It is possible that the largest craters should be classified as selenodetic phenomena. If a zone of altered rock exists below them, as has been observed in terrestrial impact craters, its extent and depth may permit classification as continental rather than regional features.

The selenodetic network and the gravimetric study of continental features belong to stages considerably later than the first few manned missions, but their importance is such that every opportunity should be used in earlier missions to collect data which will be useful in "continental" structure and regional geologic studies.

4. Priority Measurements

Priorities in lunar gravity measurements are not high since they bear little relation to hazards or trafficability except insofar as local seismicity (detectable with a gravity meter) or local voids and bubble or honeycomb structure are found to be important hazards. Gravity, in general, is a method of solving lunar geologic and selenodetic problems and deciphering lunar and terrestrial-lunar history. Thus, gravity measurements appear to be of little immediate urgency. Gravity instruments are included in early lunar missions because they will yield important scientific information at a relatively low cost in weight and time. The observations made on early missions will be important guides to later missions in which the astronauts' scope and range are increased.

Basically, the priority of gravity measurements will be determined in competition with other scientific measurements rather than with the problems of hazards or trafficability. From this viewpoint, measurements of gravity would rank below the first samples and sets of geologic observations but above or with the first use of certain geologic field instruments. The reason for this is that gravity is the only sure means of discovering anything about the moon's interior. (Seismology will not be useful for this purpose -- until a much later stage in exploration -- unless there are moonquakes.) This is particularly true of the measurements of lunar tides which are a key to the moon's rigidity.

5. Problems of the Lunar Environment

a. Temperature Change

The principal gravity measurement problem caused by the lunar environment involves temperature. For gravity meters, pendulums and tidal recording meters, the temperature will have to be compensated or controlled. With the exception of the gravity meter, control seems the best method for handling instrument temperature problems. This will require power, but the need can be reduced substantially by proper engineering. Gradiometers and torsion balances are less affected than gravity meters by temperature changes, partly because they operate in a much smaller dynamic range.

b. Power Requirement

Power will be required to keep gravity meters at a constant temperature (unless a compensating instrument is built in the meantime) and to telemeter the readings of a recording meter for tide-producing changes in surface gravity. The recording meter will not need a great deal of power (see Chapter V) as its cycle will be a lunar day in length. It should read to the nearest 1/10 milligal and recorded every 12 hr or so; presumably, the readings could be stored and/or telemetered.

c. Field Operation

A gravity meter or gradiometer for operation at the landing point presents no operational problem beyond being readable from inside a space suit; for this purpose, a galvanometer rather than an optical eyepiece readout should be developed.

Field operation of gradiometers requires a flat terrain for several meters around the observation point (see Instrumentation on the following page). If no such flat places are found, gradiometers will be of limited use.

Field operation of gravity meters requires that the relative elevation of the observation point be measured. This is usually done with ordinary surveying instruments such as a transit and rod but could be done with the aid of a specially designed camera (refer to Chapter IV, Section C).

6. Instrumentation

a. Gravity Meters

Terrestrial gravity meters, especially the widely used quartz sensor type, are small, light and not unreasonably delicate. The most popular model is a cylinder about 1 ft high, 6 in. in diameter and weighing 6 lb. It can be set up and read in about 2 min. With certain adaptations, this instrument could be made appropriate for lunar use; the beam position would be read with a pointer instead of through an eyepiece, the dial reading recorded photographically or on tape and the temperature compensation extended to cover lunar temperature ranges. Preliminary experiments seem to indicate that temperature compensation is feasible, though a certain amount of research will have to be done before a field model can be built for astronaut use. A lead time of perhaps a year will be required, working at a 2-1/2-man level.

An alternative to increasing the temperature-compensation range would be to maintain the meter at constant temperature but, as this requires energy, the former course will be better. Calibration is another lunar gravity meter problem. A steady gravitational field equal to that of the moon can be produced on earth only by letting an object move downward with 5/6 the acceleration it would have if it were falling freely, and this can, of course, be maintained only for seconds. The way to calibrate a lunar meter on earth is to tilt it so that the component of the earth's field acting on the mass in the meter is in the lunar range. This requires some precise engineering but should be feasible. A meter so calibrated will be field-tested in terrestrial gravity by removal of a mass which can be restored when the instrument is to be used for lunar work.

Specific data for instrumental dimensions, weight and power requirements are given in Chapter V.

b. Vertical Gradiometers

A prototype vertical gradiometer promising resolution of about 1 Eötvos has been built, showing the feasibility of such an instrument for lunar use. Its principle is simply measurement of the difference in reading between two gravity meters separated by a short vertical distance. This configuration avoids the need for temperature compensation, since both elastic units are at the same temperature. Thus, the instrument should be comparable in weight and dimensions to the gravity meter itself. Also it avoids the operating problem of measuring the elevation, since the vertical gradient of gravity changes only slowly with elevation instead of rapidly as does gravity itself. On the other hand, it is affected more strongly by nearby topographic features than is the gravity meter and, in fact, will not be useful if suitable stations cannot be found. A suitable observation point for a gradiometer would be a smooth, level area 10 meters or more in radius, with no irregularities of greater vertical dimension than, say, 1/2 meter. For instance, a 15-ton boulder whose center of gravity is 1 meter above the level of the instrument and 10 meters away would cause a terrain correction of 1 Eötvos. Whether places flat enough for gradiometers can be found on the lunar surface is presently unknown but, before the first manned mission takes place, more information on the question should be available.

Estimated lead time for producing a lunar vertical gradiometer is one year at 2-man level.

c. Torsion Balances

The Eötvos torsion balance is a horizontal gradiometer which, when read in several positions, measures the curvature of the equipotential surface of gravity as well as the magnitude and direction of the horizontal gradient. The field model used in the late 1920's and early 1930's was not developed further because 2 hr or more were required to read it; it was virtually abandoned for exploration purposes and superseded by the field gravity meter. The horizontal gradiometer has, like the vertical gradiometer, the advantage of not requiring an elevation correction and the disadvantage of requiring smooth terrain. If it is found that suitable smooth spots exist, it probably would be desirable to develop for lunar exploration a short-period torsion balance that could be read in minutes instead of hours. A year of work at the 2-man level probably would suffice to develop such an instrument.

d. Pendulums

Pendulums are more cumbersome than gravity meters and require a longer time to read. Their advantage, however, is that they do not require calibration in a lunar gravity field before being used to measure that field, since the variable to be measured is time. If the length of the pendulum is known, gravity can be computed directly from the period of oscillation of the pendulum. For the first several lunar missions, it probably will be sufficient to depend on the calibration of the gravity meters used but, at some stage in the lunar exploration program, it will be desirable to check this calibration against an absolute determination by pendulum. A lunar gravity pendulum can be read inside the LEM and therefore needs no extensive modification for lunar use. A year at the 3-man level probably would be required to develop such an instrument.

e. Tidal Gravity Meter

To observe lunar tides, a telemetering recording gravity meter should be emplaced at a suitable location and designed to send signals indicating changes in the local acceleration of gravity for a period of one or more lunar days. As the rate of change will be very slow, the most efficient form of operation probably will be to record the displacement periodically and telemeter the accumulated record at appropriate intervals such as every 100 hr.

The present earth-tide meter, too cumbersome and vulnerable for lunar use, would require redesign and modification and probably conversion to the quartz-sensor form. Essential to the lunar tide-recording meter would be:

- Stable displacement readout
- Linear and predictable drift
- Long-term programmed adjustment of null position if necessary
- Short-term adjustment to null position to provide readout
- Filter for excluding short-period seismic motion such as moonquakes
- Temperature compensation plus low-power thermostating as in present geodetic gravity meters

The design of such an instrument does not seem to entail any serious problem, but the lead time required is probably 18-24 months at the 3-man level because of the need to make long-term stability tests. The chief operational problem probably will be the power needed to keep the instrument at constant temperature during at least one lunar cycle.

A recording gravity meter would serve as long-period seismometer as well as tide-meter, simply by using the unfiltered signal. This would require continuous recording instead of interval readings and, hence, a heavier power consumption which might or might not be desirable according to availability of power and suitability of the instruments designed specifically as seismometers.

7. Conclusions and Recommendations

a. Recording Tide-Meter

A gravity meter for recording and telemetering gravity changes caused by the tides should be included in the SIP.

b. Gravity Meter, Absolute

A gravity meter for observing absolute gravity at the landing site should be carried with all missions and read either in the LEM or on the ground close by. Such an instrument probably can be developed in a year. Absolute calibration presents a problem. Experiments should be conducted to determine whether a pendulum would be a more accurate gravity meter than the standard elastic-member type for absolute determinations. Development of the absolute meter for lunar use should be guided by these experiments.

c. Torsion Balance

A torsion balance should be developed for lunar use and read at the landing site on the first mission. This can be done inside the LEM. If it appears that flat places for reading the instrument in the field can be found, torsion balance observations should be made whenever the astronaut approaches such a location. Use of torsion balances in exploration will depend on the exploration requirements that are developed.

d. Gravity Meter, Relative

As soon as surface traverses are made, along which the relative elevations of the stations can be measured, relative gravity should be measured. Whether this will require an instrument other than the absolute meter described above will depend on whether pendulums or the elastic-element meter is chosen. The latter probably would serve as a relative meter as well. If the former were chosen, the relative gravity meter would have to be a separate instrument.

The need of the gravity meter for use in specific exploration problems will depend upon the order in which such problems require solution and the possible contribution of gravity methods to each.

C. THERMAL MEASUREMENTS ON THE LUNAR SURFACE*

1. Introduction

Among the unknown parameters characterizing the lunar surface and subsurface, temperature and thermal properties play an important role. The existence of surface temperatures substantially above or below current estimates may present a hazard to accomplishment of lunar exploration missions and modify understanding of the nature and history of the lunar surface. Properties such as thermal conductivity, thermal diffusivity and emittance are important to clarify the nature of the surface and to provide information for lunar basing and trafficability analysis.

Estimates of lunar surface temperatures have been made by two techniques--measurement of infrared and microwave emission. Reviews of the measurements have been presented by Baldwin (1963) and Kopal (1962). Measurements in the infrared are regarded as valid for determining the surface temperature; surface temperature variations from 110° to 390°K (Murray, 1964; Shorthill, 1961) have been reported in recent years. The lower temperature limit is difficult to obtain precisely because of the low emissive power of the surface and noise level of the system. The temperature of the subsolar point varies with the moon's phase; measurements indicate a temperature range of about 350 - 407°K (Sinton, 1962) which may be attributed to the surface roughness. Microwave emission measurements have shown that the temperature of the subsurface layers varies much less than the apparent surface temperatures (Krotikov and Shchuko, 1963). The mean microwave temperature at a depth of 1/2 to 1 meter is near 220° K; however, temperatures vary from about 195° to 310° K (Sinton, 1962). There is some discrepancy as to the characteristic depth corresponding to measurements at various wavelengths. Thus, both the surface and subsurface temperatures are not known with great precision. It should also be pointed out that the measured temperatures are average values for fairly large areas of the lunar surface. Within the measured areas, there may be significant local inhomogenieties in temperature.

There have been no direct measurements of the thermal conductivity, diffusivity or emittance of the lunar surface. Values have been ascertained from comparisons of the measured temperatures of the surface with the results of mathematical analysis of models depicting the lunar surface materials (Jaeger, 1953). Generally, it has been shown that the surface material consists of a substance with a low value of thermal inertia similar to that exhibited by evacuated particulate materials or low-density foamed or sintered materials. Recent calculations seem to point to a thin layer of a pulverized material overlying a substrate whose properties are more nearly like pumice or porous rock (Muncey, 1963) or a homogeneous layer of low-density, low-conductivity porous rock (Krotikov and Troitskii, 1963). These

*Contribution of A. D. Little, Inc.

data do not give information on the individual parameters, conductivity, density and specific heat, which determine the thermal inertia. These data are not uniquely determined since it can be shown that reasonable agreement between calculated and measured temperatures can also be obtained if the surface consists of areas of bare rock among larger areas of dust, i. e., a dispersion of materials with widely varying thermal inertias (Fremlin, 1959).

The emittance of the lunar surface (in the infrared) generally has been taken to be near 1.0, although direct measurements have not been made. This value is in agreement with the observed average reflectance in the visible region (0.07) but, as with the other properties, considerable local variations can exist.

Following is a discussion of the purpose, method, requirements, and significance of the various thermal measurements to be made. Contributions of the measurements to problems of astronaut safety, trafficability, lunar basing, and origin and history of the lunar surface are rated in Appendix C. Detailed information on the instruments suggested for the thermal measurements is presented in Chapter V and Appendix D.

2. Temperature Measurements

a. Purpose

Principal objective of the temperature measurements is to obtain accurate information on lunar surface and subsurface temperatures. This knowledge will be valuable in several areas--protective systems for future missions and astronauts; heating or cooling loads on lunar structures, both on and below the surface; additional information on which to base understanding of lunar surface characteristics and lunar history; possible reactions between the astronaut's clothing and lunar surface materials; and a means of evaluating the precision and accuracy of remote methods of temperature measurement, especially earth-based measurements in the microwave frequency region.

b. Type and Scope of Measurements

Temperatures of interest are those of the surface, subsurface and deep subsurface layers; also of the support structure of the module and bootsole of the astronaut's space suit. In making surface and subsurface measurements, it is desirable to gather information from as large an area and from as many surface types as possible (for example, shadowed and unshadowed)--limitations may occur in sequential operation and data processing, as it probably will be necessary to read out many temperature sensing instruments from one control, amplification and telemetering device. Another important consideration is that the device not disturb the thermal gradient of the surrounding material nor the structure or geometry of the lunar surface material.

c. Characteristics of the Instruments

Design and use of apparatus to perform temperature and thermal property measurements depend upon characteristics of readout and telemetering equipment to be emplaced on the lunar surface. Of considerable importance are: commutation techniques; the impedance, stability, sensitivity, and gain of the amplification circuits; the availability of power and data channels; and the resolution of the telemetering devices. Potentially applicable temperature measuring devices are thermocouples, thermistors, resistance thermometers, and various optical devices (typically employing a thermocouple circuit for readout). For a given application, the choice of a device rests upon its compatibility with available readout and telemetry equipment as well as the characteristics of the temperature measuring technique itself. Because of the requirement for integration of the readout and telemetry systems from many types of measurements, this discussion will be restricted principally to the characteristics and capabilities of instruments and amplification systems.

d. Recommended Temperature Measurements

Three temperature measurements are proposed for the early APOLLO missions:

- Bootsole temperature
- Vehicle support leg temperature
- Surface temperature

1) Bootsole Temperature

Since the information obtained from this measurement is qualitative, a simple thermocouple-reference-milliammeter series circuit is feasible.

The temperature sensing junction is bonded to a thin copper disk (up to 1 in. in diameter) which may be permanently installed in the bootsole of the space suit. The junction and leads should form a reliable and rugged installation unaffected by shock or flexing of the boot. To minimize response time to underfoot temperature variations, the thermal resistance between junction and lunar surface should be minimized. Thermocouple materials may be copper-constantan or chromel-alumel.

Temperature of the thermocouple reference junction may be stabilized using the occupant's body temperature as a reference or one of the small, self-contained temperature references now commercially available.

Readout is performed with a miniature microammeter calibrated with a temperature scale and/or marked in colored segments. The micorammeter must be located in an easily viewed position. If other suit temperatures are to be monitored, a switch will enable a single readout device and reference junction to serve any selected station.

A thermocouple technique is well suited for this application because of sensing junction ruggedness and simple readout circuit. Use of a resistance thermometer is precluded by the difficulty of protecting the sensing element from strains caused by flexing of the boot and by the more complex circuitry required. Use of a thermistor for this measurement requires a simple readout circuit with the linear characteristics of the thermocouple circuit described.

2) Vehicle Support Leg Temperature

Principal requirement of the measurement technique is compatibility with the existing temperature-monitoring circuits of the LEM. Thermocouples or thermistors are suitable if they are adequately protected from mechanical damage and heating by rocket exhaust products. The temperature sensing element should be bonded to the support leg close to the point where it contacts the lunar surface. Thermal resistance between sensing element and support leg should be minimized.

3) Surface Temperature

A critical requirement for the measurement technique is accurate indication of the surface temperature without disturbing surface temperature gradients. In addition, it is desirable to take an average rather than a point temperature. Because of thermal radiation effects and low thermal diffusivity of the lunar surface, the temperature sensor must be an accurately positioned device of low thermal conductance and inertia with radiative properties similar to those of the surrounding media.

A resistance thermometer consisting of a 10-ft length of 0.003-in. diameter platinum wire could be lightly emplaced upon the lunar surface in a 3-ft circle. The astronaut could cover other loops with small quantities of lunar dust. The fine wire minimizes disturbance of the surface thermal gradients and indicates a temperature averaged over its entire length. The power introduced in the resistance measurement is dissipated over the length of the wire, minimizing thermal disturbances to the lunar surface. Longer lengths of wire might be used to reduce power dissipation and indicate the temperature averaged over a larger area. Emplacement of the loops is straight-forward, except that care must be taken not to introduce strains into the sensing wire.

A similar loop made with a series of thermocouple junctions would provide a temperature averaging effect and eliminate the heating effects which may be encountered with the resistance wire loop. Suitable reference junction units are available commercially. The low temperatures to which the reference temperature unit may be exposed preclude a self-contained battery, but power consumption is less than 50 μ w (0.4 v-dc input) and can easily be supplied externally.

A loop composed of a series of thermistor junctions could be fabricated but would have several drawbacks, including: (1) low mechanical strength of the thermistor beads, (2) concentration of the power dissipated during readout at the thermistor beads and (3) high impedance of the measuring loop.

3. Thermal Conductivity

a. Purpose

Principal objective of thermal conductivity measurements is to obtain information on the characteristics of the lunar surface and sub-surface materials. Although this information is not of major consequence in evaluating hazards to the astronaut on lunar exploration missions, thermal conductivity data will be valuable in several areas.

1) Trafficability

Thermal conductivity can be related to several physical properties of the lunar surface and subsurface materials. In situ thermal conductivity measurements will yield confirming data on bearing or crushing strength, density, composition, and other factors which influence trafficability. Conductivity measurements provide an alternate means of assessing these parameters to supplement direct methods.

2) Lunar Base Technology

Data from thermal conductivity measurements of the surface and subsurface layers will be useful in designing lunar shelters, buildings and landing areas, and of general importance in establishing heat flow and temperature patterns surrounding structures, equipment left on the surface and objects essential to future missions. The feasibility of using naturally occurring heat sinks and sources depends in part on adequate assessment of thermal conductivity of surface materials.

3) Origin and History of the Moon

As a secondary or confirming source, data on surface thermal conductivity and its variation with depth and location can yield information on particle size, structure, chemical composition, contact area between particles, density, interstitial gas pressure and gas evolution, and the heat balance of the lunar surface layers.

Information on particle size, structure and chemical composition will be useful in determining the amount of meteoroid infall and the changes produced in the lunar surface. Information on interstitial gas pressure or gas evolution, as inferred from thermal conductivity studies, can be used to determine if the surface materials are outgassing continually or if gases are being produced at depth in the lunar surface material. The implications of thermal conductivity measurements, including any possible variation of thermal conductivity with depth in the surface material, can be used to indicate the possible history of the moon in much the same way as petrographic and geological data.

4) Utilization of Natural Resources

The design and applicability of lunar water extraction processes, particularly those using in situ deposits, depend very much upon a thorough knowledge of the thermal properties of the water-bearing formations as well as the characteristic surface and subsurface materials. Evaluations of heat flow in water-bearing deposits and in aboveground processes require thermal conductivity values. Utilization of minerals also depends on a knowledge of these properties because of their influence in any process involving heat flow.

b. Type and Scope of Measurements

Three types of thermal conductivity measurements are envisaged: (1) surface materials in contact with the LEM; (2) surface materials at various locations; and (3) subsurface materials where possible. The first measurement can be accomplished from within the LEM, providing useful data if the mission is not completed. Measurements of thermal conductivity of surface materials should be made in several locations in otherwise undisturbed areas at several depths (if the subsurface material is relatively porous and sufficient in extent). Subsurface measurements should be made in several locations, especially where inhomogenieties occur. The first measurement should be made during the landing of the LEM on the surface; other measurements should be made by equipment emplaced by the crew after the LEM has left the surface. To study the effects of lunar period, solar radiation, etc., on thermal conductivity, measurements should be made periodically after the crew has returned to the command module and continued until all useful data have been obtained.

Performance of thermal conductivity measurements on the lunar surface rather than on samples returned to earth can be justified by the following reasons: (1) it may be impossible to duplicate exactly the lunar conditions of gas pressure and composition upon which the thermal conductivity of the materials may depend; (2) removal of samples may cause inhomogenieties and structural disturbances affecting thermal properties; (3) in situ measurements can be arranged to show variations with lunar phase, incoming solar radiation, effects of solar flares, periodic temperature fluctuations, and variation with depth and position in the lunar surface; and (4) in situ measurements will reduce the requirements for samples to be returned to earth and will give a redundancy in case of failure to obtain these samples.

c. Characteristics of Measuring Instrument

Thermal conductivity normally is determined by steady-state techniques involving measurement of heat flow between two surfaces at different temperatures usually contacting the material under study. Most steady-state equipment -- particularly for low thermal conductivity materials such as may occur on the lunar surface -- is large, bulky, difficult to operate, and requires extended operating time for the measurement (Everest, et al., 1963). Several small steady-state devices have been built but in general are not sufficiently versatile for use under lunar conditions. Furthermore, samples must be placed in the apparatus which may disturb the structure of the material and cause erroneous results.

An exception to these characteristics is provided by the thermal conductivity probe which relies on a transient measurement. The probe can be operated in situ, requires less than 1 hr for each measurement data point, can be used in a variety of materials, requires minimal power and instrumentation, and is compact and lightweight. The probe method is based upon measurement of the temperature field produced by a line source of heat surrounded by the material to be measured. The probe has been described in the literature, and the theory is well established (Wechsler, et al., 1963).

The probe consists of a heater wire, a temperature measuring device, (usually a thermocouple), an electrical insulating material, and an enclosing sheath. When thermal equilibrium is established after inserting the probe into the material to be studied, a voltage is applied to the heater and the response with time of the temperature sensor observed. Times required from

10 minutes for porous rocks to 60 minutes for low conductivity evacuated powders. Usual temperature rises range from 1 to 10°C. The required heater power varies with the thermal conductivity of the material; a variable resistance incorporated into a probe would allow a single probe to be used for the full range of thermal conductivities expected.

Emplacement of a thermal conductivity probe in a powder or low-density sintered material should not be difficult. In more dense materials, especially rocks, a hole must be drilled.

4. Heat Flux Measurements

a. Purpose

Heat flux measurements on the lunar surface will be used to: (1) confirm estimates of solar radiation, showing the potential hazard to the mission; (2) provide information for thermal balance studies; (3) provide indications of surface temperatures; and (4) by measuring changes in heat flux over extended durations using lunar surface materials and standard samples brought with the instruments, show the effects of dust accumulation, solar flares and radiation on optical properties of materials. Another desirable heat flux measurement would provide an estimate of the amount of heat emanating from the interior of the moon (an estimate of the radioactivity of the interior). The latter measurement probably is not feasible with existing instruments and will be discussed below.

Heat flux measurements will be valuable for gathering information on the nature and origin of the lunar surface and will be beneficial for subsequent lunar base studies.

b. Type and Scope of Measurements

It is desirable to measure the heat flux perpendicular to the surface, at surface and subsurface locations and in shadowed and unshadowed areas. In general, heat flux measurements should be combined with temperature measurements.

Most measurements will be made following the mission, since it will take several hours to establish equilibrium conditions with sensors in subsurface locations. Depending upon the type of surface encountered, the astronaut may not be able to emplace heat flux gauges at desired locations. In this case, surface measurements will have to suffice. Diurnal variations in heat flux should be measured periodically. A heat flux measurement on the surface also can be used to determine whether an area is illuminated by solar radiation or is permanently shaded. Heat flux will be an important measurement in conjunction with temperature and thermal property measurements.

It would be desirable to measure surface heat flow at several locations near the landing site to obtain a representative set of heat flow determinations. If possible, locations over surface materials of different types (e.g., dust and bare rock) would be chosen as well as locations in large, permanently shadowed areas and areas periodically illuminated by the sun.

The desirability of measuring the heat flux at large depths has been mentioned. Estimates of heat flux due to radioactive heating of the subsurface show an upper limit of approximately 10^{-6} w/cm^2 (MacDonald, 1962). Thus, typical heat flux meters would have outputs in the order of several microvolts and therefore be beyond present measurement techniques.

Although heat flow meters are not available to measure these low flow rates, estimates of heat flow can be made from measurements of temperature at depth in the lunar surface and of composition and type of materials. Assuming the heat flux value given above, for a froth or sintered material we conclude that subsurface temperature gradients would be approximately 0.2°C/meter and for a rock material 0.02°C/meter. Therefore, temperature measurements must be made for depths of at least several hundred meters below the depth at which diurnal changes no longer occur. Although the temperature measurements could be made with probes or encased thermistors, methods of drilling to deep zones would be required. Also, the holes would have to be filled and thermal equilibrium again established before meaningful results could be obtained. Similar terrestrial measurements were attempted by Gerard, et al., (1962).

c. Characteristics of Measuring Instrument

Instruments for measuring heat flux generally rely on measurement of temperature differences created in a medium of known thermal properties. Any temperature sensor can be used in the measurement if its characteristics are such that the heat flux is not altered by the temperature sensor. Radiative temperature sensors are usually heat flux meters which measure the flux emitted by the sample and, if the sample optical properties are known, the temperature can be calculated. Both radiative and conductive type heat flux meters usually require calibration under conditions simulating their ultimate use.

Conductive heat flow meters consist of a thin disk containing a multiple thermocouple assembly and a conductive spacer. The output is a voltage proportional to the heat flow through the disk. This type of heat flow meter is temperature sensitive.

For subsurface measurements, errors will be small if the disk is thin compared to the thickness of the dust or surface layer in which it is buried and has a high conductance compared to the surface layer material.

Errors are larger for surface emplacement because: (1) an inhomogeneity is produced at the surface, i.e., the energy absorbed at the surface is different in the area of the heat flux meter than at other surface locations; (2) the optical properties of the flux meter surface may be changed rapidly by dust deposition or micrometeoroid erosion; and (3) there is an unknown thermal contact resistance between the lunar surface and the flux meter which will cause errors in the meter outputs.

Because of the errors associated with the use of conductive type meters, radiometric heat flow meters are more suitable for surface measurements. This type of meter consists of a disk with appropriate surface characteristics, suspended above and parallel to the surface at a height sufficient so that the surface heat flow is not significantly disturbed. The theory of operation of the disk radiometric heat flow meter is discussed in detail in Appendix H. Two modes of operation are possible: (1) only the temperature of the disk is monitored and (2) a conductive heat flow disk such as discussed above is used, and the temperature difference across the disk is measured. Combination of the two modes results in a redundant system with a built-in accuracy check.

5. Thermal Diffusivity and Thermal Inertia Measurements.

a. Purpose

Principal objectives of thermal diffusivity and thermal inertia measurements are to confirm information on the characteristics of the lunar surface and subsurface, to indicate the rates of temperature rise of the surface constituents during periods of changing solar flux and to complement measurements of thermal conductivity. The thermal diffusivity ($k/\rho C$) and thermal inertia $(k\rho C)^{1/2}$ both contain the independent parameters, density (ρ), thermal conductivity (k) and specific heat (c). Independent measurements of thermal inertia and thermal diffusivity will lead to a determination of thermal conductivity and the volumetric specific heat (ρC), or alternatively, independent measurements of thermal conductivity, diffusivity and inertia will provide the same information. Since the specific heat of most minerals and nonmetallic materials is well known, it should be possible also to estimate the density of the lunar surface materials from these measurements.

Thermal diffusivity and/or thermal inertia data will be important in the areas of trafficability, lunar base technology, origin and history of the moon, and in determining the potential utilization of lunar natural resources. Thermal diffusivity data can provide information on particle size, structure, chemical composition, and contact area between particles of the lunar surface materials.

b. Type and Scope of Measurements

Thermal diffusivity and thermal inertia are parameters important in transient heating or cooling processes; therefore, standard methods of measurement of these parameters usually are transient in nature. Thermal diffusivity normally is measured by two methods: (1) measuring the temperature-time history of a sample transferred from one temperature environment to another (Carslaw and Jaeger, 1959); and (2) measuring the time-temperature history of a sample being heated by radiation from an external source (first reported by Parker, Jenkins, Butler, and Abbott, 1961). The first method is applicable to samples that can be moved to different temperature environments with ease and is not applicable to lunar surface materials in situ. In the second method, the temperature of the rear surface of a sample heated on the front face is measured. In most cases, it is only necessary to measure the temperature-time relationship; the strength of the heating source is not needed. It usually is assumed that the sample is opaque to the radiation incident on the front surface.

Thermal diffusivity can be determined (in theory) from measurements with the thermal conductivity probe. Two difficulties normally are encountered in this technique: (1) it is necessary to know the radial position of the temperature sensor accurately or to calibrate the probe with materials of known thermal diffusivity similar to that expected of lunar surface materials; (2) the contact resistance between the probe and the material under investigation produces greater errors when diffusivity is being measured than in thermal conductivity measurements. Thermal diffusivity could also be estimated from thermal conductivity measurements by the probe method, density measurements and indications of specific heat obtained from studying the composition of the lunar surface materials.

Since it is not possible to transfer lunar material physically to an apparatus or to measure the temperature of the lunar subsurface without altering its thermal properties to some degree, techniques (1) and (2) are not directly applicable. However, by a slightly different method described later, it is possible to measure the thermal diffusivity and inertia by two measurements at the surface without disturbing the surface materials. This method has advantages as applied to the measurements on the lunar surface.

The parameter thermal inertia, though useful, is not often measured in laboratory experiments. All thermal property data of the lunar surface have been related in one way or another to the thermal inertia of the lunar surface. Thermal inertia can be measured by determining the temperature-time relationship of a sample surface during or after the period in which the sample is heated by radiation from an external source.

As applied to lunar measurements, temperature-time (actually heat flux-time) observations of the lunar surface during lunations and eclipses permit determination of the thermal inertia of the lunar surface.

Measurement of this parameter on the lunar surface would be similar to measurements presently being made from the earth with use of telescopes and ultra-sensitive infrared detectors. However, measurements taken directly on the moon would provide reliable information on small areas, indicating the nature of surface inhomogeneities. Earth observations are limited in two respects: diffraction effects limit observation to very broad areas of the lunar surface; and the time rate of change of solar illumination on the lunar surface is relatively slow, permitting deductions only concerning average properties of relatively thick (deep) layers of lunar surface material.

c. Conceptual Methods of Lunar Surface Diffusivity Measurement

The two quantities of interest are thermal diffusivity $(k/\rho C)$ and thermal inertia $(k\rho C)^{1/2}$.

1) Diffusivity

To determine a quantity requires ultimately the measurement of its component dimensions. Diffusivity can be shown to have the dimensional units of distance squared per unit time. Thus, no matter what experiment is contrived, a determination of diffusivity will require ultimately the measurement of a distance and a time.

Thermal diffusivity measuring methods that do not require altering the material (such as by the insertion of a thermocouple) use thermal radiation alone. Radiation incident on the sample from an external source can be used to cause a thermal event in the material, the result of which is observed by radiation, in this case radiation emitted from the sample. The first such technique, "the flash method," was reported by Parker et al., (1961) and in a number of subsequent papers. In this technique, a laboratory sample, a wafer of the unknown material, has flashed onto its front face a beam of radiation from a xenon lamp or a laser source. The time of travel of the resulting heat wave through a known thickness of the sample (wafer) is observed.

Examination of this technique shows there is no variation of this 1-dimensional heat-flow method by which the measurements could be made from the front face of the sample alone, i. e., without some measurement at some depth in the material. The fact that single surface measurements are impossible in a 1-spatial-dimension method is a natural consequence of the fact that a length as well as a time must be measured in determining diffusivity. Thus, the laboratory technique is not directly applicable as a nondisturbing technique to be carried out at the lunar surface.

However, a radiation technique utilizing lateral heat flow is applicable to the determination of thermal diffusivity of lunar material. A flash method that uses radiation illumination and observation of the front surface alone is also a nondisturbing technique. To illustrate the simplest configuration, if a single small spot on the lunar surface is flash-illuminated and the horizontal surface component of the resulting heat wave observed as it travels out from the spot, sufficient information can be gathered by observing temperature as a function of time and distance from the spot to deduce a value of diffusivity for the material. The specific value of input heat--the energy level of the flash or the absorptance of the particular lunar surface of interest--need not be known.

A modified flash radiometer is proposed to make the thermal diffusivity measuring, utilizing lateral heat flow. It consists of flashed radiative heat source suspended above the surface, an optical system to focus the radiation of the surface, and an array of infrared detectors to monitor the lateral progression of the flash-induced thermal wave. The apparatus is described in more detail in Chapter V.

2) Thermal Inertia

Thermal inertia can be measured by a variation of the technique described earlier for measuring thermal diffusivity and, in fact, using the same apparatus. Thermal inertia can be determined without knowledge of distance; i.e., it can be conducted at the surface of a flash-heated material on the basis of temperature-time observations at one spot, for example, the center of the flash spot. Thus, a number of observations physically displaced from each other are unnecessary. However, the measurement of a heat flow is required. Thus, in practice, some measurement or estimate of the flash energy and the lunar surface absorptance is required.

The modified flash radiometer used to measure thermal diffusivity can also be used to measure thermal inertia. Only one infrared detector is required, arranged to monitor the radiation from the center of the flash spot. The data needed includes the time history of the emitted radiation from the flash spot region, together with estimates of input flash heat to the spot and lunar surface absorptance.

6. Surface Emittance Measurements

Emittance of the lunar surface would give information valuable to lunar basing technology in view of the importance of the emittance in heat transfer processes on the lunar surface. Measurements of emittance, expecially where desired to determine the effects of wavelength, are complex and require fairly bulky equipment.

Reflectance measurements probably are the most direct and require the least equipment. It is estimated that a considerable effort is required for design and development of instrumentation suitable for measurements on the lunar surface. Initial measurements could be made on materials returned to earth, provided structure and texture of the surface material can be preserved.

7. Interstitial Gas Pressure Measurements

Measurement of gas pressure at the lunar surface (i. e., on the surface) and within the upper layers of the lunar surface material would show the outgassing characteristics of the surface and , if the gas composition could be determined, would provide valuable information on the origin and history of the lunar surface. These measurements would aid in assessing how to use lunar resources if water or other useful materials are found in the gas. Knowledge of interstitial gas pressure would be useful in evaluating in situ processes in which vapor flow and subsurface heat transfer are important. Several types of apparatus for measuring gas pressure within a powder or porous material have been considered.

The relationship between gas pressure and thermal conductivity in a powder is well known. In the region where the mean free path of the gas molecules is approximately the same as the interparticle distance, the thermal conductivity of the powder varies considerably with changes in gas pressure. This relationship can be used to make a sensitive vacuum gauge The line heat source technique can be used to measure the conductivity of a standard reference sample of powder material. The powder and the line heat source can be contained in a small capsule (approximately 1/2 in. x 3 in.) and placed on or within the lunar surface material. Pressure equilibrium is established by means of passages in the powder container. The thermal conductivity can be measured by the line heat source method. The instrumentation, power requirements, type of outputs,and measurement time are identical to the thermal conductivity probe discussed earlier. From a previous calibration of the pressure guage in the laboratory under controlled conditions, the gas pressure can be obtained.

The type guage discussed is suitable only for pressures above 10^{-4} torr. Hence, it would be placed in regions of suspected volcanic activity in order to detect gas diffusion or flow. Development of reliable devices for this measurement would be a major effort, but would provide significant information.

D. SEISMIC

1. Definition and Scope

Seismic observations are observations of acoustic energy transmitted through the earth (that is to say, of oscillatory ground motion). Such motion is classified according to its dominant period of oscillation; on earth its periods range from less than 1 sec to the order of 1 hr. Seismic observations on earth are worldwide in scope. Explosions and earthquakes are observed from the immediate neighborhood of the site or focus to halfway around the earth. Seismic observations on the moon will have a similar scope, though logistics will limit those involving explosions rather than moonquakes. The distance between shot and observation point will extend as lunar surface mobility increases.

2. Basic Physical Principles

Observations of seismic motion are governed by three basic principles:

- The law governing the response of an inertial sensor to motion of its frame
- The theory of assuming oscillatory motion as the sum of a series (or the integral of a continuum) of sinusoidal motions of varying amplitude and period
- The laws of propagation of mechanical energy through more or less elastic material. (Such motion is propagated in compressional, shear, surface, and guided waves; it has velocity characteristic of the medium and the mode of propagation mode; it undergoes refraction, reflection, dispersion, diffraction, and attenuation. Deductions about source and transmitting medium can be made through observation of the motion.)

3. Type of Phenomena To Be Measured

Seismic observations take the form of a record of ground motion. Following are the different types of ground motion to be observed.

a. Natural Motion

1) Seismic noise

This is the more or less continuous ground noise observable at all times on the earth. Its components are lumped together as microseisms.

The principal sources of earth microseisms such as wave and wind motion are absent on the moon, but others may be present, perhaps due to meteroid bombardment, tidal motion or volcanism.

It is important to measure lunar microseismic ground motion because of the activities or phenomena it may evidence. Long-period terrestrial microseisms are thought to be due to the ocean; short-period ones, to atmospheric disturbance. Since neither ocean nor atmosphere exist on the moon, any microseisms which may be observed will be evidence of other processes.

The most likely cause of a more or less continuous level of microseismic noise on the moon would be the tidal forces. These are (as explained in the preceding section on gravity) approximately four times as great as on earth, and the resulting solid tides may have an amplitude of several meters. It would be remarkable if such a yielding of the moon's body did not produce microseisms. If microseisms due to tidal motion are observed, they will, of course, be identifiable by the cyclic character with minima at "slack tide."

If volcanic activity exists on the moon, it will cause local and time-variable microseismic activity. Besides being of great scientific interest, volcanism offers the best hope for a source of water on the moon. For this reason and until it is proved that volcanism is absent, every lunar mission should have the means to detect and record microseismic motion. If microseisms with any chance of having a volcanic origin are observed, steps should be taken then to find out whether the intensity varies with location.

2) Moonquakes

Defined as specific seismic events in contrast to a more or less continuous motion of the ground, moonquakes are analogous to earthquakes in that they send out acoustic wave trains of limited duration and characteristic form. It is important to discover whether moonquakes occur and, if so, to interpret them to gain information about their sources. Earthquakes can be caused by volcanic explosions or by stress release in the earth; the energy for both these phenomena comes from the release of radiologic heat in the interior. If moonquakes occur, they will be due to the same energy source and will prove that the moon is not a cold body and that heat transfer and therefore strain exist in it.

The possible heat budget of the moon and the level and type of seismicity that would result from various assumptions concerning it have been studied extensively. A brief summary of these results is given by Kovach and Press (1962) with a short bibliography. They point out that under the assumption that the moon's material contains radioactive elements (K^{40}, Th^{232}, U^{235}, and U^{238}) in the same proportion as chondritic meteorites, the seismicity due to radiogenic energy would be comparable to that of the earth. It is, therefore, probable that moonquakes exist and will be a valuable index both to the history of the moon and to its body structure and composition. In addition, study of their phases and travel paths will furnish, as on the earth, information about the moon's interior that can be obtained in no other way.

Moonquakes can be caused by meteoroid impacts as well as internal energy. It has been estimated (Kovach and Press, 1962) that the number of meteorite impacts on the moon detectable as moonquakes is of the order of 1 to 10 per year.

b. Induced Motion

Induced motion of the ground, as in terrestrial geophysical exploration, is caused by percussion or explosion for the purpose of deducing information about the ground structure. It usually is divided into the direct or refracted mode, in which the arrival time of head waves is measured, and into the reflected mode, in which a much later arrival due to reflection is observed. Refractions are observed easily, but observable reflections are found only in special circumstances.

The techniques and purpose of observing induced seismic motion on the moon are closely analogous to the practice of terrestrial exploration seismology. The scale ranges from tens of feet to hundreds of miles. Energy for the large-scale programs is derived from the detonation of tons of explosives, while smallest-scale observations may be activated by percussion. The object of terrestrial exploration seismology is to explore the crust down to and including the upper boundary of the mantle.

Lunar exploration seismology will be limited in scale by the cost and hazard of transporting the necessary explosives and in quality by the absence of sedimentary rocks. Nevertheless, it will be a useful tool for discovering subsurface layering of any kind, from bedrock down, and for finding anomalous features such as intrusions, low-velocity zones under impact craters, possible ice masses, etc. Obviously, small portable sets of instruments for seismic exploration will be useful in determining the depth from surface to bedrock, the character of such rocks, and existence of various kinds of anomalous bodies below the surface. These applications are called direct or refracted head-wave measurements or, simply, refractions.

It is characteristic of refractions that their effective penetration is of the order of 1/5 to 1/10 of their "spread" or distance from shot to seismometer. This means, for example, that measuring the depth to the earth's mantle, perhaps 30 km requires surface distances of 200-400 km. These distances entail use of large charges which, while possible though expensive on earth, clearly will not be feasible on the moon until an advanced stage of exploration is reached.

A second seismic exploration method is to observe a reflected wave instead of a refracted one. In terrestrial exploration, discontinuities such as the contact between sandstone and limestone are found to reflect seismic energy and, whenever such reflections can be observed, they are used instead of refractions. This is advantageous because it can be done with shot point and seismometers close together and because it requires much less explosive. On the other hand, reflections, not being head waves, are subject to seismic noise interference. For this reason, they are observed only in favorable circumstances, in particular where the reflecting discontinuity is a contact between two sedimentary layers and when the surface consists of either water or sediments broken by weathering. In the absence of these conditions it is not possible to predict whether seismic reflections will be observable -- so, even though discontinuities with suitable acoustic contrasts exist on the moon, they may not be observable with reflections.

4. Priority Measurements

The priority of seismic measurements on the moon will be considered from three different points of view --- hazards, resources (especially water) and scientific information.

a. Hazards

Any measurement promising to give information, positive or negative, about a hazard to the astronaut has priority over other measurements, as long as the hazard has not been shown to be extremely slight. There is a probability (though not a high one) that seismicity, perhaps due to the tides, may create a hazard to the footing of the astronaut and even the stance or attitude of the LEM. By terrestrial analogy, the caldera of an active volcano such as Kilauea contains certain physical hazards. Such hazards usually are detectable through ground motion observation with a seismometer or a gravity meter. For this reason, a rough measure of local seismicity should have priority over purely scientific measurements, though it is not thought likely that the moon's surface is seismically so unstable as to be hazardous.

b. Lunar Resources and Lunar Bases

The importance of local volcanism -- inevitably accompanied by seismicity -- to the exploitation of lunar resources, particularly a possible source of water, already has been discussed. Local seismicity measurements, therefore, have priority ranking with other observatories concerned with the establishment of lunar bases.

c. Scientific Measurements

Scientific seismology ranks high on the list of measurements to be made for scientific purposes for the reason that the existence (or absence) of moonquakes will indicate whether the moon is cold or hot and thus will influence the planning of experiments almost from the first. In addition, as with gravity, seismology is a guide to the moon's interior, inaccessible to all but geophysical means and yet important to the spread of knowledge of lunar, lunar-terrestrial and solar-system history.

5. Problems of Lunar Seismology

Problems of lunar seismology divide themselves naturally into adaptation of instruments to the lunar environment and operation on the lunar surface.

a. Adaptation

1) Hardening

Adaptation of seismic components to the lunar environment consists of "hardening" the components, principally to changes in temperature, and redesigning for minimum weight and power requirements. Hardening will proceed along lines already established and used in testing electronic components for use in space vehicles and probes. The problems, if not already solved, appear to be soluble. Redesign is always possible but, in the case of seismometers for lunar use, considerable effort has been spent (see the following instrumentation discussion) on the design of lunar seismometers so that extensive redesign is apparently not necessary except for systems to be used as portable exploration seismographs. Here again, miniaturization of components can proceed along lines established by the electronics and exploration industries, in which weight, volume and noise level of amplifiers and the like have been greatly reduced and reliability and ruggedness greatly increased.

2) Transportation

Exploration seismology on the moon will be limited by transportation or logistics as much as by the difficulty of providing seismic energy sources. Unless reflections are found useful, which seems unlikely, penetration to a given depth will require a surface range of five to ten times that depth. Clearly, until lunar surface transportation is available, seismology will be confined to exploring at depths of a fraction of a mile.

3) Energy

Energy for passive seismology is no problem, since it will come from natural processes in the moon as explained previously. Energy for exploration seismology poses a difficulty in proportion to the range or distance between shot point and recording points. (For reflection work, the critical range is not horizontal distance but depth to the reflector.) Terrestrial seismology may be conducted with hand-power percussion devices at very short range -- less than 100 yd --but any greater range requires use of stored energy, either to power a percussion device such as a "thumper" or to provide an explosion. For lunar seismology at ranges requiring stored energy, dynamite or some similar explosive will be the most convenient way to provide energy, but explosives will have to be brought to the moon as a part of the payload and, in any quantity, will constitute considerable hazard. This will limit seismic exploration, at least for the first few missions, to short-range experiments to ascertain facts about velocities and discontinuities in the near subsurface layers. These experiments can be conducted terrestrially with dynamite charges of 1 lb or less. The estimate of charge weight may have to be revised for the lunar ground because it is certain to be dry and may be unconsolidated to an unknown depth. Exploration at ranges of miles may require hundreds of pounds of dynamite per charge and thus be impractical on early missions.

b. Operation

The problems of seismic operation on the moon are serious on three counts -- coupling, energy and transportation.

1) Coupling

In the present state of knowledge of the lunar surface, it is impossible to predict steps required to achieve suitable coupling between the seismometer and solid ground. Seismometers for passive use on the earth usually are set from 1 to 5 meters below the regular surface to avoid the "weathered" material and to place them on bedrock. Something of the sort probably will have to be done on the moon, since it is thought that the surface may consist of light brittle material and may be coated with dust. If caves or fissures are present, it is possible that bedrock can be found in them with no excavation or, at any rate, less than is necessary for surface emplacement. Seismometers for active exploration have higher natural frequencies; on the earth, they can almost always be emplaced by hand, sometimes with the aid of a spike to which they are rigidly fastened and which is pushed into the ground. This may or may not suffice on the moon, depending on what conditions are found there.

6. Instrumentation

a. Seismographs for Natural Noise

Seismographs for unmanned landing on the moon have been designed (Kovach and Press, 1962; JPL, 1962; Kovach et al., 1963) to operate at both short and long periods. These instruments were intended to be landed by the Ranger or Surveyor missions and therefore had to be built to fall and then adjust themselves automatically. Seismographs for manned missions need not be so elaborate, though they must still be able to telemeter their signals and to remain in operation in spite of the lunar environment.

Main considerations in designing a lunar seismometer are (1) element type, (2) temperature stability, (3) pick-off for seismic signals, and (4) power supply. Of these, element design is probably the easiest to resolve. The vertical oscillating element probably will be the conventional LaCoste-type (1935) zero-length spring configuration. The horizontal-motion elements will be either the conventional swinging-gate type (Press et al., 1958) or the vertical pendulum zero-length spring type (Romberg, 1961); the latter is not so sensitive, in its period, to tilt. The springs in these elements can be either quartz or metal; if they are quartz, the moving mass will have to be very small, precluding use of the self-powering type of conventional electromagnetic pick-off. On the other hand, the quartz seismometer will be much smaller and lighter and can be made self-compensating for temperature.

Temperature stability is considerably less of a problem with seismometers than with gravity meters because no significance is attached to the precise zero position. In the case of the vertical-motion unit, a change in temperature results in a change in zero position unless an adjustment or compensation is made. Since the zero position need not be exact, it is probable that approximate compensation is the easier and more satisfactory solution to the problem; this can be done with a counterweight as in metal-spring gravity meters. Compensation is not necessary for the horizontal-motion instruments, as their zero position does not change with temperature unless they are not level.

The pick-off for seismic signals can be either a velocity-responsive or a displacement-responsive type. The standard velocity-responsive type is, of course, the electromagnetic; besides being self-powered, it may drift without changing the zero of the record. The displacement pick-off may be either the electro-optic or the capacitance type; both require power and a feedback system to return the beam to null if it has a long-time drift. Since this involves an adjustment--always a source of trouble--it is probably desirable to use the electromagnetic pick-off; the weight introduced by its mass is made up for, at least in part, by the lower power requirement. The extra simplicity is an additional advantage.

The final problem-- power supply --will depend on the configuration and the telemetering mode. It probably will be easy to record for a time and then transmit at a greatly accelerated rate to save transmission power.

A long-period seismometer designed by JPL for lunar use has been successfully tested. It is possible, however, that a simpler and therefore more reliable design could be evolved for a model that did not have to set itself up or survive a difficult landing. Such a development, beginning where the JPL model leaves off, would require 8 to 10 months.

b. Seismographs for Active Exploration

Seismograph systems for use as terrestrial exploration tools have been developed extensively for all scales of operation, from small-scale bedrock probes to instruments for recording energy that has penetrated as deep as the earth's mantle. They vary considerably in bulk and weight, depending on the required sensitivity and the mode of transportation available. However, all such systems must contain the following elements:

- A source of acoustic energy (can be mechanical, percussive or explosive; the latter is usually used because it is compact and efficient whereas percussive devices for large-scale work are cumbersome)

- A device for emitting an electrical signal at the time the energy enters the ground
- A set of ground-motion sensors, usually very short-period velocity-sensitive seismometers
- A set of filters and amplifiers for treating the seismometer outputs
- A recording device producing an oscillogram or other record of the ground motion sensed by the seismometers
- A timing device, usually integral with the recorder, for measuring time intervals on the oscillogram, especially the travel time of the acoustic energy between the source and sensor
- A source of electrical energy, usually batteries, for operating the amplifier and recorder

In order to adapt terrestrial exploration systems for use on the moon, it will of course be necessary to "harden" the components for lunar environment. In the case of passive seismometers, this presents no more serious problems than are encountered in the communication and telemetering systems for use in the LEM. For active exploration, however, the explosives, the oscillograph and electrical energy sources present problems in hardening for lunar use, largely because chemical as well as electrical action occurs. As well as can be projected from present experience, for instance with the behavior of batteries and photographic materials in space probes and with new types of cable insulations, these problems are soluble.

Next in importance to hardening is the problem of reducing the weight and bulk of the exploration systems. Portable systems have been devised for terrestrial use in which the weight has been reduced for carrying in marshes and other difficult terrain. These could be simplified and lightened further through use of the latest advances in electronics and through redesign with materials especially suited to lunar use. Such redesign would come under development and engineering rather than under research, as the instruments now available are perfectly capable of performing the task except insofar as it is to be performed on the moon. Provided hardening for such use can be prescribed, most of the design could be in advance as no crucial experiments would be needed.

7. Recommendations

a. Seismicity Package

A seismometer package for monitoring both noise and moonquakes should be included in the payload of an early mission -- the first, if possible.

b. Exploration Set--Short Range

A short-range seismograph set with energy furnished manually should be included on the first mission in which the astronaut goes an appreciable distance from the LEM -- say 100 yd. This package will be highly portable, except for the recording device which may be left near the LEM and used only for depth ranges of a few feet. Use of instruments of this character has not been fully developed for terrestrial application, partly because equipment usually is available for probing the near subsurface mechanically. A small research program needs to be conducted to determine how feasible it is to use hand-operated energy sources. In addition, the possibility of using explosives, perhaps in accident-proof capsules, should be investigated.

c. Long-Range Seismic Exploration

A long-range exploration seismograph set should be developed by making present sets lighter and more portable. By the time long-range exploration seismology becomes practical from the standpoint of transportation, more will be known about the lunar surface so that problems of coupling, energy transmission, explosive requirements, and priority information will be easier to solve. There should be a miniaturized radio communication link between shot and recorder to eliminate the need for stringing wire.

E. MAGNETICS

1. Definition and Scope

Magnetic observations on the moon will consist of measurements of changes in the total magnetic field or its components and their gradients in both space and time. Primary objective of the first is to determine the existence of the magnetic field. At the moment, based on limited evidence and certain theoretical considerations, it is believed by some that the moon has either no magnetic field or a very small one. However, this is not necessarily so, and the reasons are discussed here and in the section on magnetotellurics (p. II-51). The scope of magnetic measurements, both in time and space, will be limited only by logistic considerations for the various missions. Observations at a single station, two closely adjacent stations, at intervals along first short and then long traverses and eventually over a small and then larger area will all be useful to solve problems of composition, structure and the figure of the moon. Eventually, as magnetic surveys are carried over larger areas, a moonwide magnetic network will be established.

Measurements of the change in magnetic field with time, first at any one location and then at a plurality of stations, will yield significant data; these can be applied to solve a variety of lunar problems and to obtain a better understanding of magnetohydrodynamic problems in space. This will be discussed in more detail in the section on magnetotelluric methods. Diversified application of lunar magnetic data to solve scientific problems can be obtained from three types of experiments: those that determine surface and subsurface physical properties; those solar system phenomena measurements that best can be made beyond the appreciable influence of the earth's atmosphere, magnetic field and/or gravitational field and on the back side of the moon; and those experiments requiring a space environment for their conduct.

2. Basic Physical Principles

Assume as a hypothesis that the moon has a magnetic field and then, for purposes of investigation, the same principles used to describe the earth's magnetic field are applicable. As a first assumption it can be stated that the moon behaves like a giant magnet and its field is that of a single, large magnetic dipole situated in the core but not exactly at the center. The magnetic field at any point on the moon's surface can be described by stating its direction and strength. Any irregularities in the measurement of either the total field or its components can be attributed to a combination of exogenic and endogenic causes. The latter will be a function of the various types of material comprising the moon. The measured magnetic flux from an anomalous body is caused in part from the externally applied field and in part from the fact that the body itself is polarized. In general, the intensity of magnetization, I, is related to the magnetic field strength, H, by the formula

$$I = kH$$

where k is called the susceptibility. In this regard, the magnetic field at any point can be described in terms of the amount of magnetic flux which it produces. The magnetic field strength, H, and this flux, B, are related by the equation

$$B = \mu H$$

where μ is the permeability. If the field strength is expressed in Oersteds, the flux will be in Gauss. For the moon as well as the earth, the field strength will be much less than a Gauss. Hence, for measurement purposes, the unit most commonly accepted is the gamma which is equal to 10^{-5} Gauss. The phenomena of susceptibility and permeability often are confused in practice. It should be remembered that the former refers to the ability of a body to become magnetized, whereas the latter describes the ease of passing flux through it. However, the two can be related by the formula

$$\mu = 1 + 4\pi k$$

A further complication is introduced in the interpretation of magnetic data because the total magnetism of magnetic materials may consist of induced and remanent components. Induced magnetism disappears when there is no external magnetic field. The remainder, natural remanent magnetism (NRM), may be due to several causes which are discussed thoroughly by Nagata (1961). The NRM of igneous rocks is due mostly to thermo-remanent magnetization (TRM) which is acquired by material during cooling from high temperatures in the presence of a magnetic field. In general the cooling starts above the Curie temperature of the material, i.e., the temperature where ferromagnetic material becomes paramagnetic. Sediments may also display NRM, called detrital or depositional remanent magnetization (DRM), due to deposition of ferromagnetic grains in the presence of a magnetic field. In these cases, the direction and intensity of the NRM are controlled by the direction and strength of the external field (the earth's or the moon's field). The total magnetic effect measured thus reflects a combination of induced and remanent magnetism. A measure of the ratio of these two components is important in furnishing a clue to the paleomagnetic history either of the moon or of a buried meteoroid if one is involved. Hence, the complexities of the lunar magnetic field necessitate various measurements of the magnetic properties of the rocks as well as of the lunar magnetic field.

This is necessary to obtain a complete understanding of lunar magnetic phenomena and their relation to solution of the various types of problems tabulated in Appendix B and processes and properties listed in Appendix C.

3. Types of Phenomena to be Measured

a. Single Point Observations

1) Absolute Value

The first magnetic observation should be measurement of the total magnetic field or the vertical component at the landing site, depending upon which type of instrument is selected. This value will serve as Lunar Magnetic Base No. 1. Observations of the total magnetic field or vertical component should be at least every 5 to 10 min for the duration of each mission to determine the change in magnetic value with time. These observations can be used to obtain an idea of the variation in magnetic field with time. They can be applied to obtain a better understanding of these fluctuations in terms of their correlation with similar changes on earth for the same observational period.

In the interests of long-term study of the moon, magnetic bases should be established wherever other scientific measurements are made. As the number of these bases increases, a better understanding will be obtained of the lunar magnetic field, as well as correlations of variations in magnetic values with time, as a function of changes in lunar geology at the various sites. Initially, a reading accuracy of plus or minus a gamma would be useful, particularly if the value of the lunar magnetic field is small.

2) Gradients

Observations of horizontal and vertical magnetic gradients on the moon's surface may be deferred until later missions, because the resulting information is not as vital for an understanding of lunar structure composition and shape as it is for gravity measurements. Such observations, find their principal application later in increasing the resolving power of magnetic measurements to determine the edges of shallow geologic features which might be associated with either water-bearing strata or minerologic deposits of possible value as construction materials in lunar basing.

3) Susceptibility

Susceptibility measurements should be made of lunar surface material in place and subsequently of samples on earth. Information from these measurements is of primary importance to determine if the magnetic field measured over an appreciable area on the moon is caused by indigenous lunar material at the surface or if it is a result of a meteoroid buried at depth in the surveyed area. If the latter has a remanent magnetic field (reflecting magnetic conditions on the astronomic feature from which it was originally derived), this phenomenon could be measured even if the moon had no indigenous induced field. As more susceptibility data are obtained in the future for various types of lunar material, they can be used to obtain a better understanding of the feasibility of using magnetic surveys to differentiate between the various types of material of which the moon is composed.

4) Ratio of Remanent to Induced Magnetism

Measurements of these properties, made originally on the moon and subsequently on earth for various types of lunar material, will result in important information. It can be used to solve problems concerning the origin of lunar materials and of lunar paleomagnetism and history.

5) Time Series Observations

Observations of the changes in the lunar magnetic field with time will be important to solve problems related to the nature and origin of both exogenic and endogenic components. In addition, this information, when correlated with observations made simultaneously on earth, can be applied to solve broad problems in the field of magnetohydrodynamics as it applies to the earth as well as to space. As subsequent observations are made at different places on the moon, these data will attain even greater importance to increase the definitiveness with which these problems can be solved.

b. Magnetic Surveys

Magnetic surveys will be useful to obtain data, not available from surface geology, regarding the existence and nature of geologic structures and their composition not apparent on the surface. They have widespread application for this purpose on earth and can be used to good advantage for analogous purposes on the moon. This applies particularly for studying features whose magnetic susceptibility varies appreciably and, hence, can be detected and defined in this manner. Therefore, initially magnetometers and subsequently gradiometers will be essential to any systematic study of the lunar surface. Magnetic surveys first will be made on a small or local scale, then on a medium or regional, and eventually on a large or "continental" scale, depending upon the depth and extent of the subsurface targets and the local or regional nature of the problem. Nongradient types of magnetic surveys with a specific target must go well beyond the target's horizontal extent to provide a suitable background of information to define the anomaly properly. For example, they should cover an area several times greater in diameter than the depth of the target structure. Hence, because of the lack of mobility, initial lunar magnetic surveys will deal only with the definition of local features. Subsequently, as astronaut stay time becomes longer and both manned and unmanned roving vehicles are available, more extensive exploratory surveys will be possible and increasingly longer and larger features can be explored.

Magnetic surveys are sufficiently important, so that they should be conducted routinely by an astronaut moving on the lunar surface. The instruments are lightweight and easily read in a short period of time. Other instrument types can be provided with continuous readouts. It is emphasized that these measurements should be made both in time and space. Magnetic surveys are particularly applicable for the early missions, since they do not require accurate elevation information at the stations as do gravity surveys.

1) Local Magnetic Surveys

These surveys will be the key to subsurface selenologic structure, particularly at shallow depths, wherever there is an appreciable difference in magnetic susceptibility between target and surrounding material. They will provide means to discover the presence of meteoroid features having a remanent magnetism derived from a previous astronomical body, assuming that there is no appreciable magnetic induced field on the moon itself.

When subsequent surveys are made for water-bearing structures and those that might be used for lunar-basing materials, gradiometer-type surveys will be required. The accuracy of the measurements required is of the order of plus or minus one gamma for the nongradient type surveys and there will be no need for accurate elevation data.

2) Regional Magnetic Surveys

These surveys will be useful in subsequent missions but will not be feasible for early landings. They will provide a better understanding of the difference in composition between larger structural features of the moon such as maria and mountain areas; also, determinations as to whether the large lunar features are composed primarily of acidic or basic materials and as to the location of possible igneous intrusions. In general, areas composed of acidic materials will have a smaller magnetic field than those of basic because of the difference in their magnetite content. Magnetic surveys currently are used on earth for this purpose to good advantage.

If the moon should have a strong regional magnetic field, it could yield a clue as to the structure of its core, analogous to the dynamo theory of the origin of the earth's magnetic field. This, in turn, might provide useful corroborative evidence for lunar convection currents.

3) Selenodetic Magnetic Measurements

These measurements are analogous to those made on earth to obtain a magnetic map which is used by mariners for navigation purposes. If the moon has a sufficiently well developed magnetic field, such a selenodetic magnetic map might be used for similar purposes on the moon. Although it is unlikely that the map will be used for navigation purposes, it would be helpful in later missions to improve the resolving power of magnetics to explore for smaller structures. The minor contribution of the latter to the magnetic field could be subtracted from the regional magnetic field on which they are superimposed.

4. Priority Measurements

Priorities for lunar magnetic measurements will not be high in early missions from the standpoint of their contributions to hazards or trafficability. However, as more magnetic base measurements are made and a better understanding of lunar magnetic fields and properties are obtained, together with improvements in the prediction of solar flares, a constant monitoring of changes in time of the magnetic field might yield diagnostic criteria as to the onset of a solar flare. This then would give the astronauts an opportunity to take whatever appropriate safety measures that may have been devised against this hazard.

The primary reason for including magnetic instruments in the early lunar missions is that they will yield important scientific information and help solve major questions about the lunar environment, composition and origin with a minimum expenditure of weight and time. The various types of measurements and problems which can be solved by magnetic measurements are outlined on Tables II-1 through II-3. Observations on early missions will be important guides to subsequent activities when the scope and range of the astronauts' activities are increased. Hence, the priority of magnetic measurements for early missions will be determined in competition with other scientific measurements, rather than on the basis of hazards or trafficability problems. These are the basic reasons for ranking magnetic measurements lower than obtaining the first lunar samples and sets of geologic observations, but higher than other scientific measurements and experiments requiring more weight, volume and power.

TABLE II-1

LUNAR PROBLEMS TO WHICH FUNDAMENTAL MAGNETIC MEASUREMENTS AND EXPERIMENTS WILL APPLY

1. Chemical Composition
2. Internal Constitution
3. Surface Origin
4. Paleomagnetic History
5. Origin of Earth-Moon System

TABLE II-2

MAGNETICS (INCLUDING MAGNETOHYDRODYNAMIC PHENOMENA)

Fundamental Measurements and Experiments

Directed Toward Determining:

Presence or Absence of Magnetic Field of Moon (if present)	Intensity
	Variations in Intensity With Time and Space
	Ratio of Induced/Remanent Components
	Susceptibility-Permeability
	Curie Point of Representative Rock Types
Magnetohydrodynamic Effects Associated With Solar Flares	Intensity
	Direction
	Periodicity
	Frequency

TABLE II-3

SPECIFIC MAGNETIC PROPERTIES AND PHENOMENA TO BE MEASURED

1. Susceptibility
2. Permeability
3. Ratio of Induced/Remanent Magnetism (preferably from oriented samples from surface or cores)
4. Total Magnetic Field and/or Basic Components
5. Gradient Measurements of Magnetic Field

5. Problems of the Lunar Environment

a. Temperature Change

Magnetic instruments are not as sensitive to temperature changes as those used to measure gravity and will not require power specifically for this purpose. However, they will be susceptible to the normal effects of wide variations in temperature causing expansion and contraction of their parts. This assumes that the magnetic instruments will not be of a type requiring a magnet which is extremely sensitive to temperature changes but which will be operationally dependent upon such sensing devices as nuclear precession and/or optical pumping phenomena.

b. Power Requirement

The power requirement for actual operations will be small, of the order of milliwatts, for those instruments which the astronaut will read. Additional but relatively small amounts of power will be necessary for recording types and for telemetry. Magnetic measurements for time series purposes also will require slightly more power, since observations should be made at least every 5 to 10 min initially. These time requirements are necessary because of the rapid changes of the magnetic field with time, particularly those of exogenic origin. Details of weight, power and volume of the recommended instruments are in Part II, Chapter V and Appendix D. These measurements should also be made to within plus or minus one gamma both for the visual and recording types. They could be stored and transmitted in conjunction with other measurements, using a multiplexing system for optimum power and time-sharing purposes.

There are other possible problems involved in measuring magnetic properties of samples obtained on the moon after their return to earth because of magnetic disturbances that will be encountered while returning through the Van Allen belt, as well as the effect of the much larger induced magnetic field of the earth. While it is theoretically possible to protect the samples against these changes by using some type of Helmholtz coil system, this probably will not be practical from weight, power and volume limitations during initial missions. It becomes desirable, therefore, during later missions when there is sufficient weight available for scientific instruments, to take along equipment to measure the magnetic properties of the specimen on the moon and then measure them on earth to define the importance of these effects on the accuracy of the measurements.

c. Secular Variation

It will be a long time before this phenomenon can be studied on the moon because of the necessity of making observations over many years. However, even the first magnetic measurement made on the moon will be a start in such a study because, upon returning periodically to the same location, data will be obtained that can be used subsequently to study this phenomenon.

Even if the assumption is correct that the moon has no magnetic field (Dolginov, et al., 1961; Dauvillier, 1962) as a result of its chemical and structural characteristics, there is still the possibility that it will have a measurable magnetic field produced by exogenic forces and/or the remanent magnetic field of buried meteoroids. An example of the former is the magnetic field associated with solar flares. It has been established experimentally that interplanetary fields of 50 to 100 gamma are associated with them. Too, it is possible that a lunar magnetic field would be confined by solar wind to a thin layer above the sunlit surface, but it could extend a considerable distance beyond the surface on the side away from the moon, according to Neugebauer (1960). It has been established also from geomagnetic studies that the earth's magnetic field extends with appreciable intensity for many earth radii into space and that the moon may be included within the critical distance.

d. Magnetostrictive Effects

It has been established both experimentally and empirically that shock pressures cause well-defined changes in magnetic susceptibility. Bancroft et al., (1956) have demonstrated that this effect is not linear. For example, susceptibility of mild steel disks and on magnetite bearing grout was found to decrease with increasing shock pressure up to 120-130 kilobars but to increase again with higher pressures up to 165 kilobars -- the highest pressure attained in these experiments. In addition, experiments by Eichelberger (1960) demonstrated that shock pressures cause changes in both magnitude and direction of magnetization. Similarly, Short (1964), in studying variations in rock properties of material affected by nuclear explosions, found a correlation between changes in magnetic susceptibility and distance from the detonation area.

These facts are important in developing criteria to resolve the question of meteroid impact origin versus cryptovolcanism of geologic features on both the earth and moon. For example, corroborative evidence for a possible decrease in magnetic susceptibility from meteorite impact may account for the results of an aeromagnetic survey of Brent Crater reported by Beals et al., (1963). A marked difference exists between the magnetic intensity observed within, as compared with outside, the crater area. Only a small magnetic gradient averaging about 50 γ/mile occurs within the crater area as compared with an average of more than 150 γ/mile outside the crater. Although a part of this difference can be attributed to the thickness of crater fill overlying the basement rock, the remaining effect could reflect the effect of shock associated with the impact and explosion of the meteorite. This could disrupt the systematic dipole arrangement of the magnetic material, causing a random distribution of magnetic poles within the materials comprising the brecciated zone and hence a decrease in magnetic susceptibility and associated magnetic field intensity.

e. Field Operations

The magnetometer to be read at the landing site presents no operational problem beyond being readable within the constraints of the space suit. The output to be read can be in the form of a dial reading on a meter. These measurements also are facilitated by the fact that no elevation data at the initial and subsequent points are necessary to their use. However, the magnetometer should be read a sufficient distance from the LEM so the values are not affected by any artifically induced magnetic field from associated electrical fields. The exact distance can be determined by making magnetic measurements while still on earth around the LEM to a point where the electrical field no longer affects the readings. In this regard, at least for early missions, the magnetic field generated by astronaut life support systems, communications and possible space suit construction could act also as magnetic background noise sources. This could be a sufficient problem to require placing the sensing head some distance from the astronaut but could be determined on earth by suitable tests and measurements.

6. Instrumentation

a. Magnetometers

Magnetic instruments to be used can be placed in two major categories: (1) portable types which can be set up by the astronaut and read on a point-to-point basis, both in time and in space--for subsequent missions this type can be modified to record magnetic data continuously while traversing over the lunar surface in vehicles or on a rocket platform that can fly over the moon's surface or in a lunar orbiting vehicle; (2) stationary types which can be set up by the astronaut and turned on to record unattended for either the duration of a mission or to operate continuously after the astronaut has left by transmitting the data by telemetry. For subsequent missions, these can be left unattended at numerous places on the lunar surface for reasons discussed previously.

The instruments vary in types of measurements they can record, e.g., total field or some component such as the vertical or horizontal and their corresponding gradients or declination and inclination. The two latter types of measurements have not been stressed for early missions because the data they yield are more limited in their application to the solution of major lunar problems than the other types. The particular parameter to be considered will depend on the objectives of the specific experiments. The magnetic instruments available now or with varying degrees of modification for lunar operations, together with the parameter to be measured and lead times necessary to develop lunar models, are summarized in the engineering section in Chapter V. Details, including weight, power and volume, also are presented there. It is evident from this information that the magnetometers currently planned for lunar operations are small, lightweight and readable in a matter of several minutes at most. With certain adaptations, they can be designed for lunar use, from the standpoint of lunar environmental constraints, with relatively short lead times.

For initial missions, the use of a total field magnetometer or preferably a 3-component type and means for rapidly measuring rock susceptibility in place are recommended because of the wide variety of geologic problems to which these data are applicable. In addition, it would be advantageous to make susceptibility measurements on the moon because the values for this property could change in transit back to earth as a result of being subjected to the comparatively strong magnetosphere of the earth. A summary of pertinent problems and measurements is discussed in Chapter V. The basic types of instruments that might be applicable are listed in Appendix D. The possibility of a magnetometer designed to be read in a borehole should also be considered for later missions, assuming a lunar magnetic field has been found on the surface. The data thus obtained will lead to a better understanding of the magnetic properties and their variations with depth directly, as well as changes with depth in the vertical gradient of the lunar magnetic field.

7. Conclusions and Recommendations

For the reasons discussed in this section on magnetics, a total field magnetometer or preferably a 3-component type and a device for measuring susceptibility in place should be included in the initial missions. The former should be so designed that it can be read visually by the astronaut and have a telemetry output. This will solve the major problem of the presence or absence of a magnetic field on the moon and the probable origin of any observed magnetic field. In addition, magnetic time series data obtained for the duration of these missions at 5 to 10 min intervals should be made. Before leaving the moon, the instrument can be set up to record periodically with the data to be telemetered on a multiplex basis with other important measurements. At least one in-place susceptibility measurement should be made, preferably at the location of the limited magnetic observations. This information is vital for reasons discussed previously.

In order for the rock samples to be most useful for paleomagnetic studies leading to a better understanding of lunar history, they should be oriented with respect to fixed lunar coordinates. Also, it would be preferable if each sample could be dislodged by nonmagnetic devices to avoid the possibility of altering its magnetic properties by a combination of magnetostrictive and extraneous magnetic field effects.

F. ELECTRICAL AND MAGNETOTELLURICS (LUNARICS)

1. Definition and Scope

Telluric current measurements on the earth consist of observations of the change in flow of large-sheet electric currents over the earth's surface. Similar measurements to be made on the moon will henceforth be called lunaric current measurements. They can best be made by a combination of a magnetometer and special equipment designed for use in normal electrical property studies of surface and subsurface materials on earth. Since the origin of lunaric currents is primarly exogenic, data from these studies also will be useful to solve problems of the origin and characteristics of magnetohydrodynamic wave phenomena.

Variation in lunaric currents in time and space will be measured within the limits of logistic constraints. Observations will start at a single location, at two closely adjoining locations or at intervals along a short or long traverse, depending upon scientific stay time and astronaut mobility during each of the initial missions. Eventually, depending on lunar surface mobility, these surveys may extend over a large area culminating eventually in a lunaric current network for the moon.

2. Basic Physical Principles

Lunaric currents, if they exist, will flow along the lunar surface in large sheets and should extend well into the moon's crust. However, distribution of current density within these sheets depends on the resistivity of the formations carrying the currents. Thus, a knowledge of the electrical properties of the moon also can be studied by this method. For example, if a lunar material of poor conductivity is surrounded by more highly conducting formations, the lines of current flow will tend to bypass the former and cause easily measured distortions in the potential gradients at the surface which are associated with the current flow. It will be possible to locate the more poorly conducting medium by first measuring and then interpreting these distortions. The converse is also true, i. e., material of good conductivity will concentrate the current flow and these effects also can be measured.

Telluric current effects on earth manifest themselves in a wide variety of frequencies, field strengths and components, and the same can be expected on the moon. Hence, when these are studied, together with local geologic conditions, the electrical properties of the moon can be determined from place to place and important knowledge about magnetohydrodynamic waves can be gained. The basic equations of La Place, Maxwell and Hertz form the major theoretical basis for analysis of telluric current and hence lunaric current data. More recently, Cagnaird has modified these basic equations to cope with geologic and environmental factors affecting propagation, penetration and other pertinent characteristics of these currents. These results can be applied also in interpreting lunaric current data to solve lunar problems. However, because of the severe environmental constraints, certain additional instrumental modifications also are needed to solve specific lunar problems. Of these, the most important is that of coupling the desired signal to the sensor. This will be discussed in the problems portion of this chapter.

The precise mechanism for generating these currents has not been definitely established. However, it is generally believed that they are induced in the earth by ionospheric currents which show some correlation with the diurnal changes in the earth's magnetic field. It is expected that the same will apply on the moon if the assumption is correct that the moon falls within the extreme outer limits of this effect of the earth. These currents cannot be measured directly, but the horizontal potential gradients which they produce at the surface can be measured and the current densities deduced in combination with resistivity studies. The study of lunaric currents on the moon is especially important because they will be unaffected by the earth's atmosphere. Hence, simultaneous observations made on the earth and moon will yield data of singular importance to an understanding of these phenomena, as well as magnetohydrodynamic waves.

3. Types of Phenomena To Be Measured

The first observation of lunar currents would be their measurement at the LEM landing site. This value will serve as Lunaric Base No. 1 and should yield information on any major compositional discontinuity with depth at this point. This can be done by analyzing the data in a manner described in a terrestrial experiment by Green and List (1963). The results of their survey conducted near Dallas, Texas, is shown in Figure II-1. The bottom trace is a record made by Texas Instruments Metastable Helium Magnetometer (Figure II-2). The two upper traces record earth current probes arranged in mutually perpendicular directions, namely, north-south and east-west. The data thus obtained were used to compute the depth to the basement in this area (Figure II-3). This is possible because of the marked difference in electrical conductivity of basement versus sedimentary rocks. A depth of 14,000 ft to the basement computed by this method agrees closely with depths recorded on logs of nearby wells.

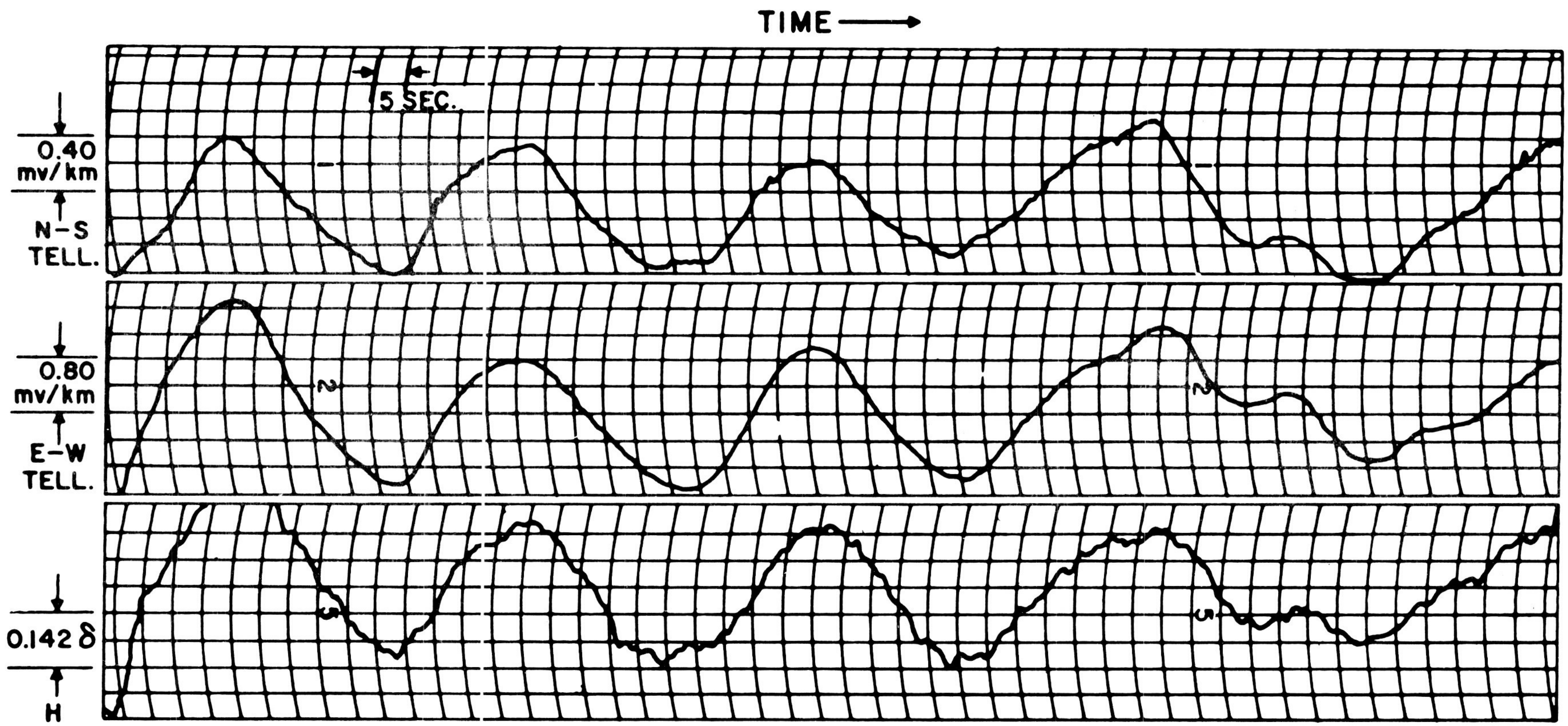

Figure II-1. Long-Period Micropulsations (50 secs) at Dallas, Texas at 2000 CST 14 May 1962 (Measured With Earth Current Probes and a Metastable Helium Magnetometer).

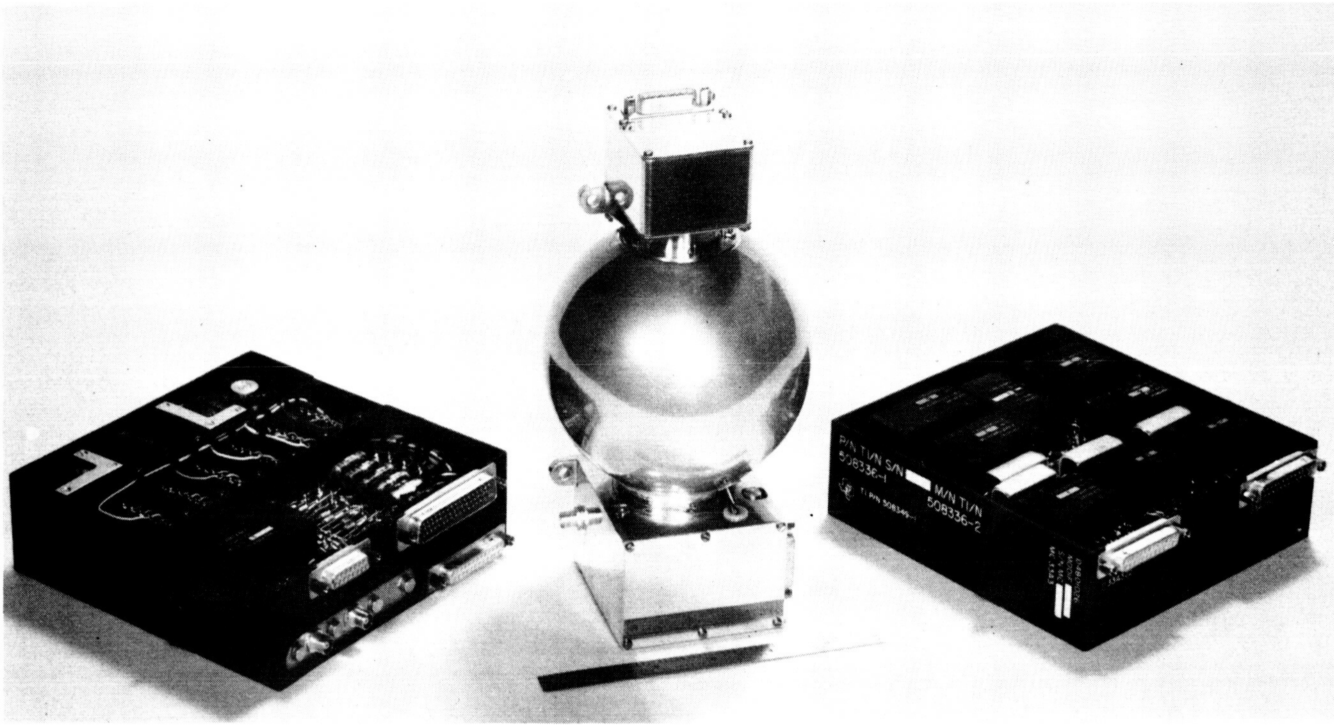

Figure II-2. TI Low-Field Metastable Helium Magnetometer.

Time series information obtained from this initial station will be useful also in magnetohydrodynamic wave studies and possibly may provide data relative to the effect of plasmas, solar wind, and to a lesser extent, shock fronts. Also, experiments requiring a large mass for shielding against the sun's radiation could be performed during later missions on the dark side of the moon. In addition, if it is determined by early missions that the moon has a low magnetic field or no magnetic field, more direct measurements of the solar stream can be made on the moon than on earth. This stream normally is deflected by the earth's magnetosphere at a distance of about 10 earth radii, and measurements on or near the earth are inadequate.

For observations during initial missions, an accuracy of ± 1 or 2 mv would suffice. Similarly, the frequencies observed during early missions of periods of the order 3 to 10 min would be satisfactory, but shorter periods of the order of seconds that might be observed on later missions would be of greater significance and could markedly improve understanding of the various types of phenomena discussed.

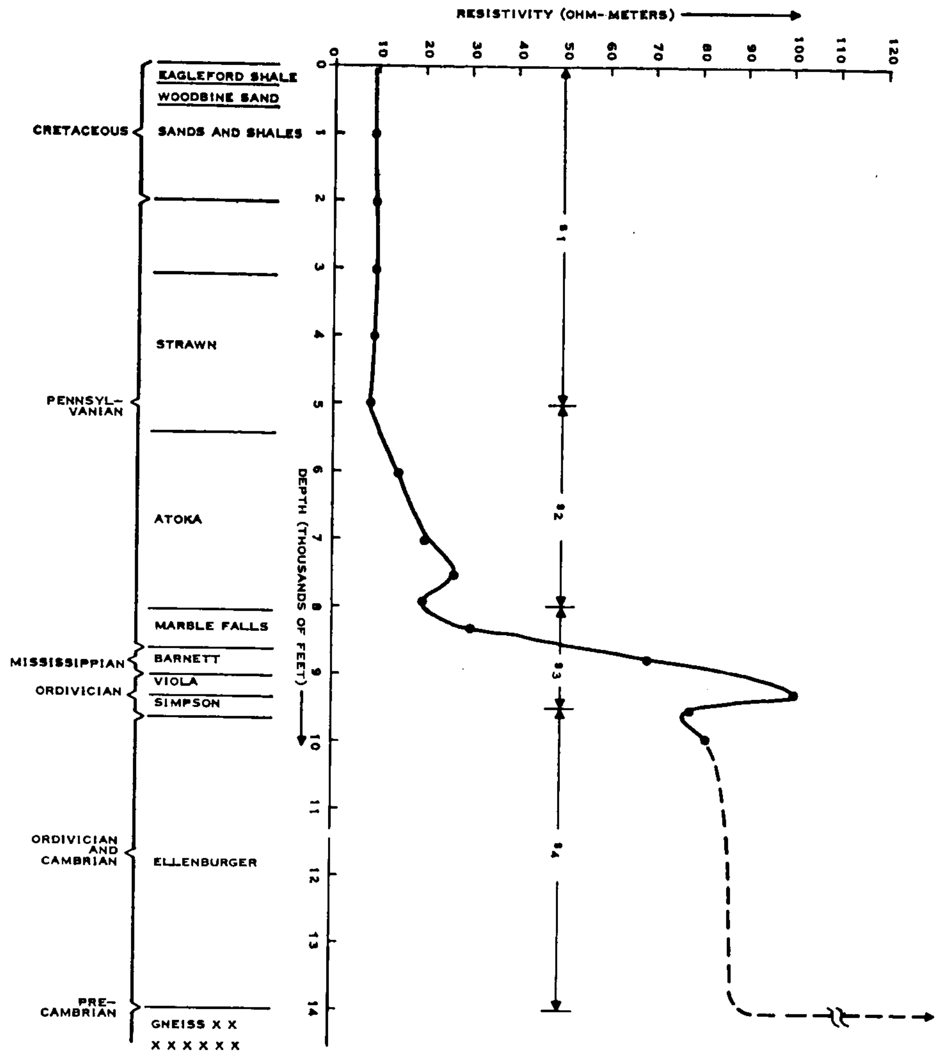

Figure II-3. Resistivity and Structural Data for Dallas, Texas, Site.

a. Lunaric Surveys

These surveys will be useful to obtain information not available from surface geology to deduce the existence and nature of subsurface geologic structures. This applies particularly to those of larger areal extent and greater depth than might be obtained readily with other geophysical methods. Lunaric current surveys have the added advantage that they do not require external energy sources, relying upon exogenic phenomena for this purpose. Thus, there is no hazard to the astronaut as, for example, there would be if explosives were to be used as an energy source for seismic methods.

Data obtained by this method also yield information simultaneously on both exogenic and endogenic phenomena. In addition, any major structural composition and change involving such large-scale features as maria and mountains could be determined when surveys using this method are made in these areas.

b. Dielectric Effects

Measurements of dielectric properties on the moon are important not only in studying electrical rock properties but also in obtaining data for use in calibrating directly results of radar studies of the lunar surface from earth. Hence, knowledge of the values of this property measured directly will increase the interpretation accuracy of earth-based radar measurements of the lunar surface. For future mission planning, a knowledge of electrical properties when combined with lunar seismic information will be very useful to obtain a better understanding of the seismic-electric effect on the moon. Assuming that rock properties are more homogeneous on the moon that on earth, the moon is a better environment in which to study this effect (Hamer, 1930, and Thomson, 1936 and 1939) because this will avoid some of the difficulties encountered in studying this interesting phenomenon on earth.

4. Problems of the Lunar Environment

The logistic problems associated with energy sources are not important because the lunaric method depends upon large-scale exogenic processes which need only be measured and not generated. Signal-to-noise ratio may become important, depending upon the magnitude of some of the secondary components of the overall energy source. These act as noise and may under certain circumstances override the signal to be studied, depending upon the particular problem under investigation.

The problem of coupling the desired signal for the conductivity sensing device component in lunaric current measurement could be formidable in the moon's environment. This is also the reason why more conventional electrical methods, including both active and passive types widely used on earth, have not been stressed in evaluating possible measurements and experiments to be made on the moon. These include spontaneous polarization and electrical conductivity and resistivity, using both direct current and alternating current, as well as electrical transient techniques. At best, the problem of coupling the electrodes used to sense these phenomena is a major one even for earth surveys. For example, it is difficult to measure true earth potentials because of electrode polarization effects which depend on the properties of the soil in which the electrodes are buried. For the moon, except in dust-covered areas, the electrodes probably would have to be inserted into rock. This would pose a drilling problem unless the rock contained sufficiently large fissures or fractures. Even then under these conditions, some plastic conducting material would have to be available in sufficient amounts to surround the electrode and make contact with the irregular surfaces of the fracture, fissure or hole. A means for transmitting the signal from the rock through the plastic to the electrode thus would be provided.

The coupling problem also poses considerable mechanical, chemical and electrical problems. Furthermore, it is generally difficult to separate the polarization caused by electrochemical action at the electrodes from the potential associated with telluric currents. Also, terrestrial sediments and rocks usually contain interstitial fluids which act as a medium for conducting the desired electrical signal in electrical surveys on earth. On the other hand, on the moon near-surface interstitial fluids over large areas are presumably absent -- thus complicating the problem. This also would apply to dust-covered areas, even though electrode burial would not be a problem. In addition, resistivities then would be primarily a factor of the characteristics of the rock-forming minerals. They would, however, be markedly different for those commonly measured on earth because of the major difference in temperature ranges between earth and moon. The extreme range on the moon would result in abnormally low resistivity values during lunar nights and correspondingly high ones during the day. For example, the resistivity of cosmic dust (assuming it to be iron) could vary about an order of magnitude from approximately 3×10^{-1} ohm/meter^3 for -150°C to 3×10^1 ohm/meter^3 for a temperature change of +150°C. Therefore, resistivity studies of representative rock materials in various stages of mechanical and chemical alteration should be conducted in an environmental laboratory capable of reproducing at least a major portion of this thermal as well as vacuum range.

Because of the difficulties involved in ground coupling of electrodes to study any electrical properties or phenomena on the lunar surface, emphasis should be given to use of capacitance methods not requiring electrode planting. One of the more important examples of these methods is the AF-MAG type used extensively for mineral exploration on earth. The same suggestion applies to instruments for measuring the dielectric constant for use in radar studies. A schematic diagram is shown in Figure II-4. (Fritsch, 1949).

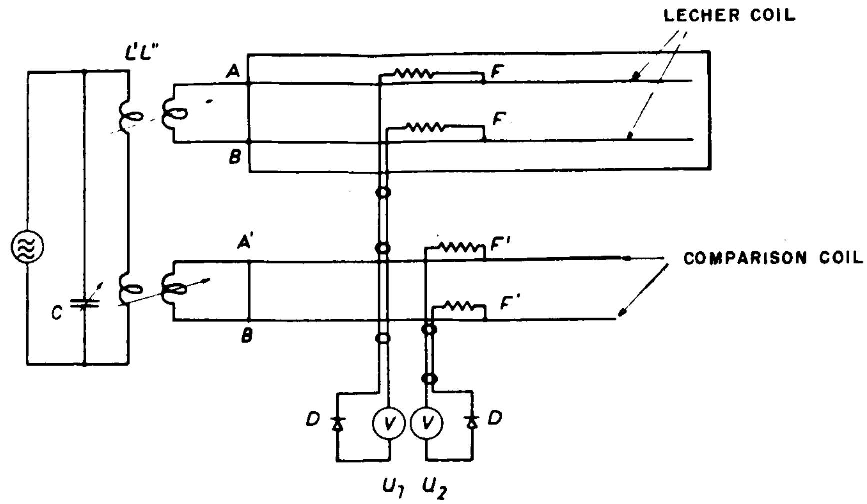

Figure II-4. Dielectric Constant Measuring System

Anisotropic effects also are an important factor in understanding the resistivity of major rock units, but it will be a long time until sufficient resistivity data on the moon are available to consider the contribution from such effects in the interpretation of the geologic significance of lunar electrical methods.

5. Priority Measurements

Every effort should be made to devise means to overcome coupling difficulties, particularly if it is learned in early missions that the moon lacks or has a weak magnetic field. In terms of resolving power of available magnetic instruments, it then will be necessary to rely upon lunaric current and electrical surveys to solve problems of lunar composition, structure and origin outlined in Tables II-1 through II-3 of the Magnetic section. Furthermore, electrical methods are particularly suitable for defining the outline of shallow geologic features which might be important as a source of water or materials to be used in future lunar basing. The various types of information and problems soluble from magnetotelluric and electrical methods are outlined in Tables II-4 to II-7. Early missions should be confined to obtaining measurements from the wire loop system in conjunction with magnetometer readings as described previously. The results can be used to solve problems in magnetics and magnetolunarics, both endogenic and exogenic, discussed elsewhere in this section.

The power requirements for these instruments are very modest compared with other geophysical methods, and the estimated needs are given in the appropriate places in the engineering section and charts in Appendix D. In addition, rock samples should be returned to earth where their electrical properties can be measured.

TABLE II-4.

ELECTRICAL INSTRUMENTS

Measurements	Instruments
Resistivity	D-C A-C Capacitance Electrical Transients
Conductivity	D-C A-C Capacitance Electrical Transients
Spontaneous Polarization	D-C
Dielectric	D-C A-C Capacitance
Magnetolunaric Current and Magnetohydrodynamic	Wire Loop Zero Field 3-Component Magnetometer Flux Gate Magnetometer Proton Precession " Helium " Rubidium "
Seismic-Electric Effect	Any A-C, D-C, Capacitance or Electrical Transient Instrument System Together With Artificial or Natural Lunar Seismic Source
Anisotropic Effect	Any A-C, D-C, Capacitance, Electrical Transient or Spontaneous Polarization Instrument System Making Measurements Both Parallel and Perpendicular to Strike of Lunar Geologic Featuring Being Studied in the Field or for Rock or Core Sample
To be Developed for Lunar Environment	Self-Reading Devices Telemetering System
Maximum Simplification of Field and Instrument	Procedures To Facilitate Astronaut Reading and/or Activation Making Necessary Observations

TABLE II-5

LUNAR PROBLEMS TO WHICH FUNDAMENTAL ELECTRICAL MEASUREMENTS AND EXPERIMENTS WILL APPLY

1. Chemical Composition
2. Internal Constitution
3. Surface Origin
4. Paleomagnetic History
5. Origin Earth-Moon System
6. Criteria for Short-Term Warning System for Occurrence of Solar Flares
7. Effect of Ionosphere and Earth's Atmosphere on Magnetohydrodynamic Waves (results could be applied to predicting their effects on communications)

TABLE II-6

ELECTRICAL (INCLUDING LUNARIC CURRENT PHENOMENA)

Fundamental Measurements and Experiments

A. Measure Basic Properties in Place and/or Subsequently on Samples Back on Earth Including:

   1. Resistivity-Conductivity
   2. Spontaneous Potential (if possible)
   3. Dielectrics

B. Measure Lunaric Currents Generated by Solar Winds and Flares Including:

   1. Intensity
   2. Periodicity
   3. Frequency
   4. Direction

TABLE II-7

SPECIFIC ELECTRICAL
PROPERTIES AND PHENOMENA
TO BE MEASURED

1. Resistivity-Conductivity of Near-Surface and Subsurface Material
2. Spontaneous Potential (if possible)
3. Simultaneous N-S Component (with magnetometer) and E-W Lunaric Current (with probes and wire coil) Magnetic Micropulsations
4. Anisotropy
5. Seismic-Electric Effect

a. Field Operations

Requirements for this type of survey are the same as those presented in the Magnetometer section. The site should be far enough removed from the LEM to avoid its magnetic and electrical effects. The equipment for the electrical portion of the magnetotelluric method consists of two coils of wire, each 100 ft long. They are to be arranged in mutually perpendicular directions. As stated previously, the proper planting of the electrodes may present a problem, depending upon the surface characteristics of the site at which the LEM lands.

The location should be near the SIP so that the output from the electrodes can be monitored and telemetered on a multiplex basis at 5 to 10 min intervals after the astronaut has departed. Similarly, while the astronaut is there, he should read meter values at similar intervals coinciding, if possible, with magnetometer readings. There are no problems of elevation surveying as in gravity surveys, and the wires may be laid over small surface irregularities, comparable to those which would not interfere with astronaut mobility, without affecting appreciably the quality of the data obtained.

6. Instrumentation

The magnetometer that is a component of the lunaric current measurement system is described in the Magnetic section. It, too, must be situated a sufficient distance away from the LEM so as not to record any magnetic field associated with it. Similarly, the site for the two wire loops about 100 ft long, each arranged mutually perpendicular to one another with their associated electrodes, should be located so as to be unaffected by stray electrical fields produced by the LEM equipment.

The input from the electrodes should go to a recording instrument that measures the voltage drop between them due to the lunaric currents. Because, using an earth analogy, fluctuation in the RMS of the telluric field may vary from a few tenths of a millivolt per kilometer to several tens of millivolts, a low noise electronic amplifier probably will be needed in the circuit to improve the signal-to-noise ratio. There will be no problem of elevation differences as in gravity measurements. Also, the wires may be laid out over any surface irregularities, of an amplitude comparable to those traversable by the astronaut, without affecting the quality of the data.

The problem which still remains, however, is to pick an area where the coupling of the electrodes to the lunar surface will present the least difficulty, not only physically but electrochemically. Details regarding weight, power and volume requirements are to be found in Chapter V and Appendix D. Instruments for measuring electrical properties in bore holes will probably not be used on early missions but are listed for completeness in Appendix D.

7. Conclusions and Recommendations

Lunaric current studies should be given high priority during initial missions because of the diversified value of the data obtained. In addition, the magnetometer portion of the lunaric current system does not represent additional weight, power or volume because it should be included for making magnetic measurements. The wire portion of the system will not require any appreciable modification for operation in the lunar environment; hence, only minimum modification will be necessary to the recording instrument. The chief problem will still be that of coupling the electrodes both physically and electrochemically, but going far to solve it will be earth-based research that can be conducted prior to the mission.

The use of more conventional electrical methods has not been emphasized for the initial missions because of the limited application of the results of these data to the solution of lunar problems--in comparison to the requirements of weight, power and volume of the instruments and the time required by the astronaut to make the necessary observations. However, during later missions when it becomes urgent to find water-bearing deposits and construction materials for lunar basing and exploration, these methods should be reconsidered. They are particularly well adapted to define compositional and structural changes at shallow depths, which will be a primary area of interest for these purposes. However, in the meantime, the electrical properties of lunar samples returned to earth should be studied to establish criteria to decide which of the more conventional methods, either in passive or active form, will be most advantageous to conduct on the moon. These include spontaneous potential or induced polarization, as well as d-c and a-c electrical surveys. In regard to measuring electrical properties of the samples on earth, it will not be necessary to take the precautions cited for measuring magnetic properties, thus facilitating the problem of sample return and still yielding useful, accurate information.

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CHAPTER III

SOIL MECHANICS

A. SUMMARY

Presence or absence of a "soil" cover on the moon's surface will be important to future lunar operations. Absence of soil would imply difficult terrain conditions for both pedestrian and vehicular travel, as well as hazardous landing conditions, and would present severe obstacles to development of a lunar base. On the other hand, deep deposits of "dust" would be equally difficult to negotiate, but presumably could be handled as construction material more conveniently than solid rock. Available evidence indicates that a "soil" mantle somewhere between these two extremes covers a major part of the lunar surface. It will provide the principal natural construction resource, as well as a cushioning interface between landing or locomotive systems and the possibly hard, uneven surface of underlying rock.

Solutions to problems arising in the safe, efficient use of this soil mantle as a construction material and as a natural trafficable surface will be sought through application of soil mechanics principles. This technology undertakes to integrate mechanics, strength of materials, and physicochemical phenomena with scientific observation and experimentation to solve earthwork and foundation problems. It can be applied also to other problems in which the mechanical behavior of soil masses is paramount. Essential to development of a lunar soil mechanics technology is a soil classification system based on recognizable index properties which vary and which may indicate differences in mechanical properties such as compressibility and strength.

This chapter is not a comprehensive text on soil mechanics. However, it undertakes to illustrate by detailed discussion the rationale of soil mechanics and its role in the APOLLO program. This is followed by a discussion of pertinent literature and findings concerned with the nature of lunar soils. In turn, index properties are analyzed to indicate their possible value to classify and predict soil behavior and to provide background for the elementary treatment of pertinent soil mechanics theory and discussions of mechanical properties which follow. Finally, the contributions of various tests, measurements and observations in the major problem areas--Hazards, Trafficability, Lunar Basing, and Surface Origin--are discussed.

Proposed measurements and observations in lunar soil mechanics are selected to satisfy the following objectives: (a) to insure safety of a pedestrian astronaut, especially with respect to sinkage; (b) to recognize index properties which vary from place to place as a basis for

classifying and mapping soils on the moon and simulating lunar soils on earth; (c) to validate terrestrial theories of soil action such as the Mohr failure theory, Terzaghi's solution for ultimate bearing capacity, etc.; (d) to measure representative soil design factors including bulk density, the shear strength parameters ϕ and c, ultimate bearing capacity, and the density-compactive energy relationship; and (e) to determine representative values of soil depth as it affects astronaut safety and evaluation of sites for a lunar base. (The latter is essential to select appropriate structures and construction methods and to determine available borrow materials.)

Recommended instruments and tests are, for the most part, exceedingly simple and are selected to measure mechanical properties in place as well as to make qualitative comparisons of surface materials at various locations. These instruments include a simple staff, possibly augmented by a proving ring and reading dial; apparatus for measuring bearing capacity and torsional shear strength in place (modified after the Surveyor soil mechanics apparatus); a vane shear device for measuring in-place shear strength; and a camera for making various safety and familiarization observations. (See Appendix F for list of selected soil mechanics equipment.) Numerous other useful experiments are described which may satisfy advanced mission constraints or may serve as alternate objectives in the event those recommended are superseded by unmanned probes. It is noteworthy that virtually all terrestrial soil mechanics test apparatus lacks the portability and compactness essential to this program; an entire new generation of soil testing equipment, based on experimentally developed miniaturization concepts, is needed for lunar use. Terrestrial counterparts are listed in Appendix D.

B. INTRODUCTION

In a restrictive sense, soil mechanics is a basic scientific discipline concerned with the physical and mechanical properties of soil and the influence of these properties on the mechanical behavior of soils under various loading conditions. However, because these factors are so intimately related to construction practice and performance of engineering works, the usual connotation includes the soil technology applied to earthwork and foundation engineering. Ancillary activities such as field mapping, exploration and classification testing also may be considered within the scope of soil mechanics because a knowledge of the inhomogeneities of soil deposits is as important in engineering and construction practice as data concerning mechanical behavior. In addition, the distribution, variation and index properties of soil deposits are among the most important factors bearing on hypotheses of soil origin.

Applied soil mechanics is concerned with the application of scientific methods to two main types of problems, those which depend on strength of the soil and those related to deformation and volume change in soil under foundations, pavements and earth structures. In the first category are analyses of stability for embankments, cuts and natural slopes; design of footings against the possibility of breaking into the ground; and analyses of retaining walls, shoring and bracing of cuts, bearing capacity of piers and piles, and problems related to the capacity of natural terrain to support vehicles. The second area is concerned with settlement of structures and embankments which may, if excessive, produce damage through cracking and misalignment of delicate equipment. On earth the problems associated with hydraulic properties and phenomena of soils are also of concern; in fact, water is probably the most important single factor in the mechanical behavior of terrestrial soils. However, there is ample evidence that the occurrence of water on the moon will be limited to hydrated minerals in certain rocks and possibly isolated ice deposits; thus, effects of soil water have been disregarded in these studies.

The approach to practical soil engineering problems has been largely empirical in the past because earthwork and foundation designs require quantitative factors incorporating adequate margins of safety. Even so, successful application of soil mechanics principles requires a considerable amount of judgment and intuition. These can be gained only through experience in design procedures, familiarity with soils in the field and observations of soil behavior both in the laboratory and in the field. A multitude of environmental factors and complex stress conditions affecting the performance of soils cannot possibly be duplicated in a laboratory test. Nevertheless, the results of such tests form the basis for development of theories of soil action, and observation of field performance provides verification of the validity, or the limitations, of such theory.

Certain types of problems involving stress distribution within soil deposits and boundary structures can be analyzed according to the theory of elasticity. However, mathematical complexity, coupled with the variability and inelastic behavior of natural soil deposits, limit the utility of this method. Where this is the only practical approach, compensation for the inherent uncertainties is made by use of wide margins of safety in design factors to insure that critical stress conditions are never reached within the soil mass. According to Terzaghi (1943) the state of stress within a soil mass can be estimated by means of the theory of elasticity when the safety factor with respect to failure by plastic flow exceeds about 3.

Much of the value of early lunar soil investigations will stem from experience gained through contact with lunar materials and observations of the ways in which they vary. Rational schemes for classifying and mapping soils are based on factors which vary from place to place and are apt to be highly oriented towards a specific application or objective. It is possible to predict the variations which lunar soils may manifest only by analogy with terrestrial soils. Likewise, predictions of mechanical behavior, implicit in the selection of experiments and testing equipment, are largely based on knowledge of terrestrial soil mechanics, reinforced by experimental findings of various investigators who have studied the effects of vacuum and other simulated lunar phenomena.

C. THE LUNAR SOIL MODEL

1. General Discussion

Examination of various concepts embodied in models of the lunar surface proposed by other workers is necessary prior to evaluation of lunar soil mechanics tests and measurements. Selection of a "best" model is not the object of this study; rather, definition of limiting cases is attempted to identify the most critical as well as the most general problems and to select experiments and instruments yielding the greatest probability of success under the full range of conditions likely to be encountered.

Available knowledge concerning conditions on the lunar surface is obtained by matching noncontact sensor data with terrestrial models, laboratory experiments under simulated environments and philosophical conjecture. Much of this information is controversial, and some of the laboratory experiments are conflicting; nevertheless, all serious viewpoints must be considered in preparation for a manned lunar investigation. Conclusions which might be made at this stage of knowledge will certainly be subject to considerable revision as more definitive information becomes available. However, for planning purposes a model need not be consistent or accurate as long as the full range of possibilities is considered. For instance, lunar soil deposits of low density could be extreme hazards if they extended to great depths. On the other hand, shallow soil deposits, a few centimeters in depth, would present severe restrictions to development of lunar basing concepts which involve use of soil as shielding material or placement of underground facilities. Both extremes are considered in planning appropriate investigations.

2. Remote Sensor Evidence

Photometric properties have had a substantial impact on theories concerning the lunar surface. The most important properties which determine the photometric character of a material are its albedo and brightness. By comparison of the lunar photometric curve with those of various types of material in laboratory tests, it has been demonstrated, and generally accepted, that only exceptionally rough and porous surfaces backscatter light as sharply as the moon. Among the various models which closely fit the lunar photometric curve are the "peat moss" and the loosely sifted micron-size rock dust of Van Diggeln (1959) and Hapke (1963), respectively.

On the basis of such evidence, Gold (1963) proposed his "fairy castle" model consisting of a particulate system of fine rock dust in an extremely loose state, on the order of 90 per cent porosity. The soil structure developed by small particles with high surface adhesive forces could be similar to the honeycomb structure associated with certain terrestrial fine-grained soils. Gold postulated that very thick deposits, perhaps as great as a kilometer, could accumulate in the lower mare regions by agents which include an evaporation-condensation cycle, electrostatic forces and bombardment by meteorites and micrometeorites.

Hapke (1963) found that the lunar photometric curve was best fitted by an extremely porous dendritic or reticulate structure characterized by open, interconnected cavities. His particles, composed of lunar rock darkened by high energy cosmic radiation and impinging hydrogen ions, averaged 10 microns in diameter.

Halajian (1964) reported on investigations undertaken by means of an improved photometric analyzer, capable of sampling large areas. His investigations showed that the complexity of a surface which backscatters light like the moon is not peculiar to fine dust but could be equally well reproduced by surfaces having large-scale irregularities. Good agreement was obtained with sea corals, NASA slag and dendrites. He corroborated Hapke's conclusions that the surface of the moon is covered with a dark, highly porous material characterized by interconnecting cavities. Thus, instead of a surface which is smooth at 10-cm scale as postulated by Gold (1959), the lunar microrelief could vary anywhere from the wave length of visible light to 10 cm. The upper limit is that established by radar measurements of lunar terrain. Photometry reveals neither the absolute scale of roughness nor infers the consistency of the material.

Divergent opinions have evolved regarding interpretation of the evidence obtained from radar measurements of the moon. Evans (1962) in his summary of radar reflection studies concluded that the surface of the moon is characterized by irregularities in the size range between 10 microns and 1 cm. Sytinskaya (1962) determined the probable range of microrelief as 0.1 mm to 0.1 meter. Pettengill (1960) says that about 5 per cent of the surface is rough to the scale of 68 cm. According to Green (1961) the latter distribution indicates a surface which could be as rough as lava flows or have a geologically normal amount of faults and fractures.

Studies concerned with the polarization of reflected light have contributed additional evidence concerning the properties of the lunar surface material. Lyot's (1929) early investigations showed that volcanic ash reproduces the lunar polarization curve. He concluded that the moon is covered with a layer of fine dust or ash. Polarization studies by Wright (1938) verified that at least part of the lunar surface is covered with dust. He determined from early studies (1927) that powdered pumice most nearly reproduced the lunar polarization curve. Later work by Barabashov (1959) extended these investigations, with the conclusion that the best model match was obtained by powdered tuffaceous rock and volcanic ash.

Infrared and microwave measurements demonstrate that a thin layer of dust over a hard substratum may exist but do not preclude a thicker layer. Infrared and polarization measurements as well as laboratory measurements of electromagnetic parameters as a function of grain size all indicate the presence of dust less than 0.3 mm diameter.

3. Laboratory Soils Investigations

A substantial amount of synthetic knowledge already has accrued from laboratory studies of soil behavior in simulated lunar conditions. The principal factor considered has been the effect of vacuum, but other work has treated the effects of temperature and gravity on mechanical behavior of soils. In addition, investigation of the contribution of sputtering to soil-forming processes has been carried out in a vacuum chamber (Wehner, 1963).

Certain qualitative indications of lunar soil behavior can be observed through such experiments in simulated lunar environments. The greatest value acquired to date, however, is probably in the experience in techniques of environmental testing and instrumentation and recognition of problems such as elimination of gas from soil voids during drawdown (Vey and Nelson, 1963). Until samples of lunar materials are examined, there is no way to ascertain the validity of the conclusions reached through such tests or determine how well the simulated lunar materials agree with those of the moon.

Remote measurements of the lunar surface and model matching give a roughly qualitative picture, within wide limits, of the structure and physical properties of lunar surface materials but yield few facts about the mechanical properties and behavior. Experiments under simulated environmental conditions are undertaken to set limits on the behavior of these materials. A review of these experiments is included here because in essence they comprise the fabric of many scientific questions requiring answers from lunar explorers to form the scientific basis of a lunar construction technology. Academic contributions to the general store of scientific knowledge result from such experiments, but practical solutions to difficult hazard, trafficability or architectural problems are the primary objectives.

Studies of penetration in cohesionless materials have been conducted by a number of investigators, to facilitate interpretation of data obtained by unmanned probes impacting the lunar surface and establish spacecraft design constraints dictated by possible lunar soil conditions. Lunar impact probes and dynamic penetration experiments have been incorporated in several unmanned space missions, and it is essential to gain an understanding of dynamic penetration phenomena if the data from such experiments are to be fully utilized.

When a probe or penetrometer is forced into the ground, the soil in its path is displaced, and the resultant strains are propagated to an indeterminate distance. A plastic zone will exist within the region immediately adjacent to the probe, wherein the shearing resistance of the soil is fully mobilized and an obliquity condition exists; this will extend radially as far as the strains shear the soil to its stress limit. The depth to which a probe will penetrate is thus a function of the soil shearing strength, albeit a complex one.

Since penetration resistance is an index of shearing strength, it is frequently used on earth to compare the strength of soil from place to place. In trafficability measurements, penetration resistance is compared empirically with limiting-strength conditions which will afford passage of a vehicle. Since clay soils are subject to loss of strength at constant water content through remodeling, a particular number of passes are specified in conjunction with the penetrometer index value for a given vehicle. In foundation exploration, penetration is used to correlate soil conditions at various depths from place to place, and to determine the minimum depth to which piles should be driven.

The state of packing in granular soils is expressed by the relative density, $D_r = \frac{e_o - e}{e_o - e_{min}}$, where e_o = maximum void ratio and e_{min} = minimum void ratio. This condition has an important effect on the behavoir of soils undergoing shear. If initially the material is in a densely packed state, much of the shearing resistance is due to interlocking of the soil grains. As the soil is sheared, grains in the shear zone must ride over one-another, thus causing a volume increase. This expansion against the applied normal force requires energy. If the soil is in its most loose state, the volume change is negative, and a lower shearing resistance will result. If the pores are filled with fluid, part of the normal stress is carried by the fluid, thus reducing the intergranular friction. A temporary quick condition may result when the normal pressure on the failure plane is applied rapidly.

Roddy et al., 1962) demonstrated this phenomenon in experiments on dynamic penetration. Penetration on specimens of finely crushed material at low relative density was greater at atmospheric pressure than in vacuum because the hydrodynamic lag in the expulsion of air caused decreased interparticle stresses. On the other hand, in samples at high relative density, these tested at atmospheric pressure had higher shearing resistance than those in vacuum because of the additional energy required to draw air into the voids. Cratering effects noted during penetration were more severe in the loose air-filled specimens than in vacuum, confirming that negative pore pressure results from air expelled by rapid penetration of the probe. It was concluded that dynamic penetration resistance in a loosely packed granular material is less in vacuum than in air for the same sample material, probe size and drop height.

Whether or not this conclusion is pertinent to lunar soils will depend on the nature of the interparticle surface forces operative in the moon's environment. Many workers --(Salisbury, 1963; Winterkorn and Johnson, 1963; Vey and Nelson, 1963; and others)-- have observed development of flocculent structure, indicative of interparticle cohesion, in vacuum. This is generally attributed to stripping of water films and other impurities from the particle surfaces. The phenomenon of apparent cohesion in terrestrial soils results from capillary tension due to water films surrounding points of contact and molecular orientation of water films adjacent to clay particle surfaces seeming to have properties approaching those of solids. However, removal of these films in a vacuum chamber gives rise to forces which have their seat at the particle surface points of contact. The net forces may be attractive or repulsive, depending on the mineral composition of the particles (Vey and Nelson, 1963). The effectiveness of these forces in increasing shearing resistance is a function of particle size because small particles have a higher ratio of surface to mass, thus permitting a larger total area to come in contact for a given mass.

Salisbury et al., (1963) sifted a variety of mineral powders in a vacuum approaching 10^{-10} torr to observe the development of interparticle adhesion. The size range of particles tested corresponded to the size range of the cloud of particles surrounding the earth as detected by micrometeorite bombardment of earth satellites. Based on assumed ideal particle geometry and mass, and atomic bonding between particles, a shear stress of 2×10^8 dynes/cm^2 at the damage threshold was calculated. It was estimated that the shearing resistance for electrostatic bonding was 350 dynes/cm^2 at an insignificant normal pressure. No significant adhesion was observed at 10^{-5} Torr. Salisbury concluded that Van der Waals forces or ionic and covalent bonds are probably responsible for high-vacuum adhesion.

Halajian (1962) discussed evidence presented by Zhdanov (1957) that the adsorption of water films by quartz particles ground in vacuo produces permanent surface changes which are not reversed when these films are desorbed in vacuo. Comparison of adsorption-desorption isotherms of quartz particles ground in vacuo with those dehydrated by calcination in vacuo showed that a much more adsorption-active surface was formed in the quartz ground in vacuo, and indicated that the structures of the two types of surfaces are different. It was proposed that broken Si-O bonds produce electrostatic free charges which show a specific adsorption of polar H_2O molecules, whereas calcination in vacuo resulted only in removal of H_2O molecules, reaction between neighboring OH groups and compensation of valences to form closed groups like $>$ Si = O. If friction is governed by the extent to which chemically and physically held surface films reduce the contact area between particles, radically different frictional behavior should prevail on the moon--unless the surfaces are contaminated by gas films produced by some other mechanism. Ryan (1961a) points out there is no evidence that gas films do not exist on lunar particle surfaces, and it is quite possible that vaporization by impacting meterorites or effluent volcanic gases could contaminate particle surfaces. Irreversible particle coalescence and consequent changes in surface energy were investigated by Martin (1963). Water vapor sorption isotherms were measured for samples degassed to 10^{-5}mm for various isotherms of similar samples which had undergone degassing and extended storage under sealed conditions. In every instance the samples which had undergone storage showed reduced adsorption, indicating that the clay had reduced its surface energy by reduction in total surface area through coalescence.

Static bearing capacity of dry powdered basalt was investigated by Bernett et al. (1964). Samples with various particle size distributions were tested in air and in a 10^{-6} torr vacuum by means of small probe penetrometers. It was determined that packing density was the factor having the greatest effect on bearing capacity, the effects of vacuum being insignificant by comparison. Bearing capacity of loose materials requires an arbitrary definition of the failure condition. For the loosely packed material it was defined as the mass per unit area at which depth of penetration was equal to the probe diameter. The densely packed material showed an abrupt critical load point in the load-settlement curve which was taken as the failure criterion.

In contrast to these conclusions, experiments by Rowe and Selig (1962) showed an increase in both static and dynamic bearing capacities for all densities when exposed to vacuum. This phenomena was attributed to significant increase in shearing strength, especially at the higher vacuum levels.

Direct shear tests on silica flour and ground olivine performed by Vey and Nelson (1963) showed that the angle of internal friction increased slightly as pressure was decreased from atmospheric to 10^{-9} Torr Hg. This trend is significant but is far less than one might predict from results of experiments on the frictional behavior of metals under moderate vacuum (Bowden, 1952).

D. SOIL PROPERTIES AND ENGINEERING BEHAVIOR

1. General Discussion

The fundamental premise on which these studies are based holds that a particulate or reticulate, unindurated surface layer of mineral matter exists over at least a part of the lunar surface, as demonstrated by evidence previously cited. Within this category are materials of highly vesicular or fibrous form, having more or less continuity in the solid phase, which would be broken into a particle aggregate by pedestrian or vehicular traffic. This model of the soil would not include materials such as pumice and scoria which, even though highly vesicular, can support relatively heavy surface loads without crushing unless occurring as rubble in a partially disaggregated form. If the entire moon's surface should prove to be covered by solid rock material, the concept of lunar soil would not be germane, nor would the rationale of soil mechanics be pertinent.

2. Familiarization and Classification

Virtually every scientific or engineering problem concerned with soils requires a reference framework within which distinguishing characteristics and areal changes can be identified. The so-called index properties comprise the basis of field classification systems.

Ideally, certain characteristics of index properties are common to all soil classification systems:

- They are expressions of the factors which vary most from place to place, or from time to time.
- They can be measured or recognized readily without complicated or time-consuming measurements.
- They are correlative with other behavioral properties which cannot be measured as easily.
- They reflect the environmental history which has acted upon the materials in question.

To summarize, index properties provide the means whereby generalizations about the limits of a deposit and its physical attributes can be made from point measurements and observations.

Invariably soil classification systems are strongly oriented to fulfill a particular need. For example, relatively low precision is permissible in a range of soil parameters selected for purposes of trafficability and evaluation of hazards. Investigations for these purposes might employ only two index properties--perhaps depth and penetration resistance--and conceivably could be undertaken to identify and map limiting "go" and "no-go" conditions. Furthermore, either of these factors could be evaluated qualitatively by probing with a stick, provided the investigator was familiar with the operational behavior of his vehicle in a range of similar terrains, or had experienced a foot-crossing over near-critical terrain. On the other hand, a classification system designed to categorize soil deposits according to suitability for lunar base construction would involve many more factors. These would be measured more accurately to facilitate the most economical design consistent with functional requirements.

a. Preliminary Field Investigations

Development of a soil classification system for any purpose must await a determination of the conditions which actually exist on the lunar surface. Indeed, a major task, although not necessarily a difficult one, for the first mission will be to identify and define the ranges of soil parameters which can serve as index properties for future mapping activities. This can be accomplished by a general reconnaissance in which perceptive visual examination, probing and photography will be unexcelled investigative tools.

Factors which may serve as soil index properties on the lunar surface include texture, structure, color, angularity, mineralogy, slope, depth, electromagnetic properties, and results of some extremely elementary qualitative tests. Observations to answer the following questions will contribute valuable qualitative data:

1) How deep will a staff penetrate?

2) Is the surface texture that of loose dust, sand, gravel rubble, or solid rock?

3) Is the surface material characterized by a reticulate or needlelike structure rather than a particulate structure?

4) Can the material be compressed or compacted like a snowball and retain its shape?

5) Does such a specimen acquire a marked increase in breaking strength as tested by bending or crushing by hand?

6) Are there visible changes in color, texture, structure, and slope?

7) Is there a cemented crust? If so, probing to test its strength and thickness, as well as the nature of the material underneath, should be accomplished.

8) Does the material adhere to other objects and to itself? It may be useful, in subsequent missions, to take along small samples of various types of structural material such as plastics, teflon, asbestos, glass, metals, etc. to make simple qualitative tests designed to determine the range of affinities which proposed materials have for lunar dust.

9) Are large blocks, boulders, etc. evident which could be used as construction materials? Test the "heft" of a few and note the maximum sizes exposed which can be moved.

10) How deep are the astronaut's footprints? Stereophotographs and measurements would permit semiquantitative evaluation of bearing capacity.

11) Are erosional and depositional features evident, and do they evince unique structures or textures?

Each such test or observation which yields a definitive result should be supported by a photograph and narrative evaluation of the phenomena and, if applicable, the test procedure. Areal differences are especially significant.

After a preliminary reconnaissance of this type is accomplished and specific factors for use in classification are identified, detailed investigations on subsequent missions may be conducted to measure and map in greater detail those parameters which are essential for refinement of lunar basing concepts and scientific objectives.

On the first mission these observations, insofar as pertinent, probably will be made within a 1000-ft radius of the LEM. Obviously, any contact whatsoever with the lunar surface will provide part of this information. Answers to questions 1, 2, 3, 6, 7, 8, 10, and 11 can be obtained by an astronaut during the initial process of identifying hazards. Evaluation of these factors will continue as he conducts his reconnaissance over the specified mission range. Items 3, 4 and 9, which involve handling, should be deferred until it has been determined that no hazard due to chemically reactive constituents exists.

b. Index Properties

Development of lunar soil classification systems for purposes of engineering and mobility must be deferred until additional knowledge of the lunar surface is obtained. Nevertheless, it is reasonable to speculate about the factors which might be useful for this purpose and consider the means by which they can be investigated on the moon.

1) Texture

The basis for virtually all terrestrial soil classification systems (e. g., the Unified Soil Classification System developed by Dr. A. Casagrande, the MIT system, the U. S. Bureau of Public Roads system, and the U. S. Department of Agriculture system) is grain-size distribution. This is practical because: (a) terrestrial soils are primarily particulate systems, and (b) engineering behavior and workability of terrestrial soils is very closely related to particle size.

The most significant break in the soil particle size range on earth occurs at 2 microns, roughly the upper limit for materials which demonstrate plasticity. Below this point, particle size distribution is somewhat meaningless at the present state of knowledge. This is because: (a) behavior is determined primarily by surface forces, sometimes called collodial forces, which exceed gravitational forces (whose significance is reduced because of the high ratio of surface area to mass for small particles) and, (b) particle size is difficult to measure and apparently is a function of electrolyte concentration, dispersion energy and the measurement system employed. It is questionable whether the measurement of particle size has any real meaning in this range, since clay particles are inseparable from adsorbed ions and oriented water films occupying their surfaces and defy all removal efforts short of measures which destroy the lattice structure.

Texture or particle size distribution may be a practical index property for lunar soils as well, provided that particulate systems do exist on the moon. Lapilli, volcanic rubble, talus deposits, and impact ejecta appear to fit the category of materials which can be classified by particle size. Even vesicular materials, which are not particulate systems, may be considered to have a textural distribution if the vesicle size distribution is considered instead of particles normally associated with such systems. This would call for innovations in measurement, possibly making use of optical properties of such a system.

Macroscopic particle size distribution can be measured indirectly from photographs or directly by means of sieving and screening. This is certain to be one of the measurements which will be performed routinely on soil samples returned to earth. Since the test results are fairly insensitive to the environment in which they are obtained, no advantage would be gained by sieving samples on the moon. Particles in the microscopic size range pose some difficult problems with respect to measurement; sieving on the moon would probably be difficult because particles will tend to agglomerate and clog fine screens. Wet methods such as sedimentation and elutriation are not considered feasible in the lunar vacuum, and exposure to liquids on earth may have a variety of extraneous effects depending on structure, chemical composition and the like.

2) Structure

Depending on the background of the user, the term "structure" has a number of meanings as applied to terrestrial soils. Among these are use of the term to refer to the various horizons which appear in the profiles of agricultural soil series; the tendency for certain soils to break easily into small, fairly uniform chunks when cultivated; and, for the soil mechanics specialist, the geometric relationships between the smallest particles which can be identified in fine-grained soils. For the latter use, terms such as "honeycomb," "flocculent," and "disperse" structure are frequently used.

The meaning intended in this report relates to the geometric relationships between the solid phase and the adjacent voids in lunar soil. It assumes special significance because a great many hypotheses proposed concerning the nature of lunar soil favor the concept of a reticulate rather than particulate structure. Thus, the classifications inherent in use of texture do not apply. A classic difficulty in using grain size as an index parameter of materials stems from the fact this is really valid only for more or less equidimensional systems composed of discrete particles within a size range which can be passed conveniently through a sieve or screen. The reindeer moss, needle structures, whiskers, cotton-candy, and fairy castles conceived by various investigators are all beset by classification problems related to grain size because, in a true sense, grains do not exist. The structures may vary in detail, degree of fineness or randomness from place to place, and it is safe to predict that their engineering behavior will vary in like manner. Thus some scheme based on structural attributes seems well suited for lunar use. The significant factors of a reticulate system may be degree of randomness in orientation of the structures; diameters of the "recticles," whatever their nature; and areal or spatial density of the solid material. If the individual structural features of such a system prove to be microscopic, their size, like that of clay particles, will be mainly of academic interest.

Observation and photography of soil structures will be performed in conjunction with evaluation of other factors, and require no special allocations of time and resources. Soil structure can be studied in detail on samples returned to earth, provided they are not completely disaggregated during sampling and transport.

3) Color

A soil description which did not note soil color probably has never been written. This important index property is a principal means by which the identity and extent of soil mapping units are recognized, and is frequently an important indicator of genesis and parent material. On the moon, color may be indicative of the extent to which the surface has been altered by such soil forming processes as spalling, sputtering and meteoritic impact. Whatever stratigraphic changes or horizons may be encountered in the soil will possibly manifest differences in color or tone.

4) Bulk density

Variations in this property, which is a factor in virtually every engineering soil design computation, may arise from differences in mode of soil formation, history of sputtering or meteoritic impact, and parent material. In the subsurface, variations may reflect chronological changes in the depositional environment. Differences in texture and structure may also result in variations in bulk density. The most expeditious measurement of this factor would involve extraction of a cylindrical sample by a tube of known dimensions and determination of the sample weight on earth.

Gamma-ray backscattering has been proposed for measurement of lunar soil bulk density (Eimer, 1962; Canup et al., 1962). However, assuming the lunar soil minerals have a specific density of approximately 3.0 g/cc, and taking the porosity at 90 per cent as suggested by various workers, the resulting bulk density would be only 0.3 g/cc. This, unfortunately, is in a range where the response curve is nearly flat, as shown in Figure III-1 from Eimer's paper. Thus, the possibility of errors as great as 100 per cent exists in this method. Further, merely placing the instrument on the soil surface could cause marked changes in density from the undisturbed condition. For that matter, so may insertion of a sample tube.

5) Depth

Even if lunar soil should prove to be spatially homogeneous from the standpoint of most properties, it is highly probable that significant variations in the thickness of the soil layer will occur from place to place on the lunar surface. Many of these variations probably will occur in a predictable way, once the basic modes of soil information have been identified. Thus a fair amount of engineering information will be made available for site selection, borrow material prospecting and avoidance of hazards. High accuracy in measuring soil depth is not necessary for an initial reconnaissance; the information obtained through probing for hazardous conditions will suffice. It should be noted whether changes in topographic slope and position are indicative of variations in soil depth. From a scientific viewpoint it would be

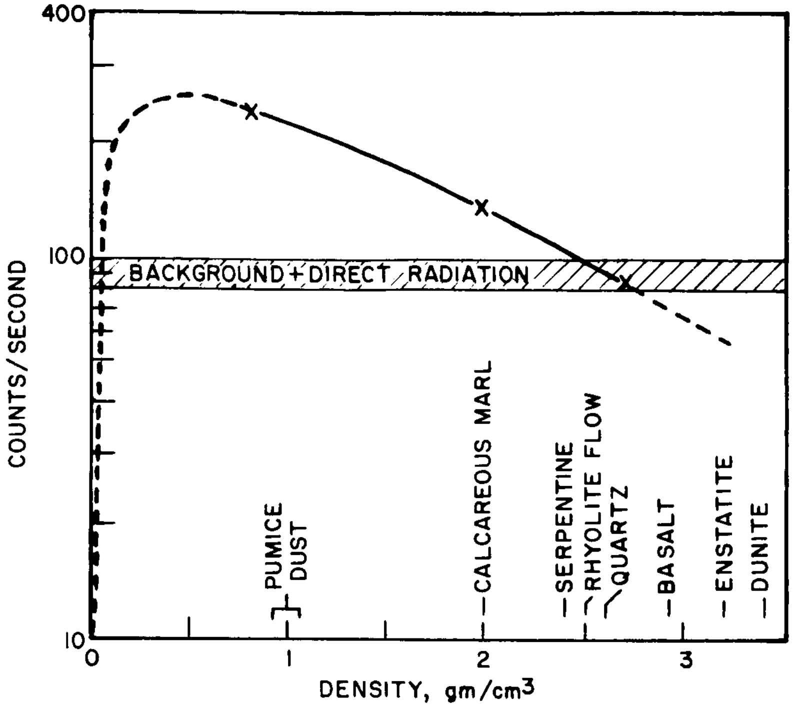

Figure III-1. Gamma Ray Backscattering Response Curve (Eimer, 1962)

interesting to know whether there are significant differences in soil depth between maria and highlands, but the limited ranges of initial APOLLO excursions will preclude such investigation.

6) Angularity

Particle angularity on earth is useful as an indicator of the erosional history and conditions of deposition of sand, gravel, etc. Aeolian dune deposits frequently are characterized by sharp, angular sand grains, whereas beach deposits and alluvial materials are more rounded and worn. Certain clues to the genesis of lunar deposits may be evident from angularity and shape as well. Consider, for instance, thermal defoliation vs corpuscular radiation as an erosional agent. Extreme rounding of particles under certain conditions might be indicative of formation through condensation of materials vaporized or melted by meteor impact. On the other hand, platy or angular particles would be more likely to result from thermal defoliation. Regardless of genetic significance, angularity influences shear strength of frictional soils and therefore merits consideration as an index property of lunar soils. No special allocation of time or resources is required to investigate this factor on the lunar surface since it can be readily studied in samples and photographs returned to earth.

7) Mineralogy

The importance of mineralogy in engineering behavior of terrestrial soils is especially apparent in those clays which undergo high volume changes with variation in water content. Other examples in which engineering behavior is strongly influenced by mineralogy include sands having a high mica content, gravel deposits in which the aluminosilicate minerals have been altered by weathering so that they degrade under traffic and compaction equipment, and loess, for which the engineering properties are largely determined by the solubility and concentration of calcareous cementing material between the soil grains.

A different aspect of mineralogy may affect the performance of lunar soils. This concerns the presence of ultraclean particle surfaces, which may exhibit tendencies to bond with other particle surfaces, depending on the mineralogy involved. Vey and Nelson (1963) found that the bonding tendency of olivine powder, as demonstrated by apparent cohesion, decreased under ultra-high vacuum levels, whereas the apparent cohesion of silica powder increased under similar conditions. It was concluded that vacuum above a certain level causes an increase in interparticle forces which may be either repulsive or attractive, depending on the material. Since no one has yet performed such tests at vacuum levels closely approaching those believed to exist on the moon, it is difficult to predict the magnitude of these forces. It is certain, however, that the coefficients of mechanical friction associated with various minerals will be vastly different from those encountered on earth, where virtually every particle surface in the natural environment is covered by a film of adsorbed gas or water. Vey and Nelson concluded: "It is probable .... that the mineralogical composition has a significant effect on the porosity of the soil on the lunar surface."

The silicate minerals are not, of course, the only ones expected to constitute lunar soils. In terms of engineering behavior and surface structure, the iron-nickel minerals may have the greatest influence. Since these metals cold weld at vacuum levels somewhat less than those expected on the moon, their presence in soils should impart exceptional characteristics which may be easy to identify and map. Although minerals ideally should be recognizable in hand specimens, as may actually be the case for "whiskers" or other particles of regular crystallographic habit, certain mineralogical properties such as distinctive color, "heft," hardness, and the like may be useful criteria for soil mapping and classification. These factors are discussed further in Chapter I (Geology).

8) Slope

Although not a soil property, this factor is included because of its possible significance in inferring the nature and depth of soil deposits which may be controlled by slope. If there should prove to be a paucity of soil on the lunar surface, a favored place for such material may be at the base of steep rock slopes, i.e., talus deposits.

The natural angle of repose is frequently regarded as indicative of a granular material's angle of internal friction. This criterion should be used with caution; it is true only when the material in question is noncohesive and occurs at its loosest packing density. The criterion has no substance in fact for cohesive materials.

3. Mechanical Behavior of Soils

In the foregoing section, various index properties which serve to describe and classify soils were examined, and their possible usefulness in the lunar environment was evaluated. In this section, a discussion of the mechanical behavior of soils will lay the groundwork for examination of various tests and measurements in subsequent sections.

The soil properties which determine its mechanical behavior are termed shear strength and compressibility. Bearing capacity is largely a function of shear strength, although it depends as well on geometry of the loaded area. For terrestrial soils another property, permeability, must be considered. However, as this report is concerned with the lunar environment, wherein the likelihood of encountering free moving fluids in the soil is extremely remote, this property will not be discussed. Nevertheless, Winterkorn and Johnson (1963) have discussed the feasibility of using various liquid reagents in stabilizing lunar soils; hence study of permeability in lunar soils may be a valid topic for investigation during advanced lunar construction stages.

The rate at which load is applied is an important variable in terrestrial soil mechanics tests including all shear test procedures, compressibility studies and the California Bearing Ratio test. Harroun (1953) noted that varying the rate of strain in a laboratory shear test between 30 in./Min and 60 in./Min resulted in mobilization of cohesive resistance up to four or five times greater than the cohesion values found at the standard rate of 0.05 in./Min, and variations of the same magnitude resulted for cohesion values measured by means of the Mark II soil truss at high shearing rates. However, this is believed to be a viscous phenomenon for which no lunar counterpart will exist. It is believed that lunar soil mechanics tests will be relatively insensitive to strain rate as long as forces are applied slowly enough to minimize inertial effects. Hence the testing times estimated for instruments listed in Appendix D are considerably lower than one would associate with terrestrial tests which are affected to a marked degree by viscous forces and pore pressure effects.

a. Shear Strength

Problems involving the shear strength of soils will constitute a major portion of lunar soil mechanics. Problems include stability analyses for natural slopes, cuts and embankments; bearing capacity problems such as evaluation of the resistance of foundations to stresses induced by loaded footings, rafts, etc.; and design computations concerned with pressures exerted by soil masses against lateral supports and roof structures. Evaluation of the support and tractive reaction supplied by the ground to vehicle locomotive systems is also within this category.

A clear understanding of the principles which underlie the concept of shear strength in terrestrial soils is essential for evaluation of their lunar counterparts. Therefore, these principles are reviewed in considerable detail in following paragraphs.

When external forces are applied to solid bodies, they are resisted by internal stresses. The total stress acting on an internal plane or section at any point in the body can be resolved into components normal and tangential to the plane. Internal stresses cannot be measured; however, in materials which obey Hooke's law, $s/\epsilon = C$, where s = stress, ϵ = strain, C = constant (modulus of elasticity), it is possible to determine the state of stress at a point from measured strains and a knowledge of the material's elastic properties. The concept of failure in such materials usually involves a well-defined yield point, or ultimate strength, so design procedures employ ample safety factors to insure that service loads never exceed these stresses.

Soils do not, in general, behave according to Hooke's law, and it is not possible to predict with reasonable accuracy the stresses induced by external loads from the accompanying strains except at very low stress levels. Most soils can sustain considerable deformations without significant loss of shearing resistance; hence they are regarded as plastic materials. This is to say that they can undergo continuous deformation at constant stress when the condition of failure is reached.

It is feasible to evaluate the stresses acting on a plane of failure from the loads known to have caused failure. Conditions of rupture can be characterized by an appropriate theory of failure, and the limiting stress conditions existing at failure can be determined by a laboratory test under conditions similar to those existing in the field. The design or stability analysis then involves determining stress conditions at failure in a test sample and comparing the conditions with those imposed on various possible failure surfaces by the design or service loads.

It is usually assumed that the shearing resistance of a soil mass is related to the normal stress on any plane by Coulomb's empirical equation

$$\tau = c + \sigma \tan \phi \tag{1}$$

where the symbol c represents the cohesion or shearing resistance per unit of area when the normal stress on the failure surface, σ, equals zero. The parameter ϕ is called the angle of internal friction; its role is analogous to the coefficient of sliding friction between solid bodies. The parameters c and ϕ can be evaluated by means of laboratory tests in conjunction with the Mohr failure theory.

In general, all planes through a point in a solid will have both shearing and normal stresses. A fundamental principle of mechanics states that through any point three orthogonal planes exist on which there is no shear stress. These are named according to the magnitudes of the direct stresses acting on them as major, intermediate and minor principal planes. Since critical values of normal and shearing stress always occur on planes normal to the intermediate principal plane, it is convenient to disregard the intermediate stress condition and work with a biaxial stress system.

Consider the elemental force system in Figure III-2, in which the major and minor principal stresses, having intensities σ_1 and σ_3, act on planes at right angles. This is the same condition which prevails in a triaxial shear test, wherein an all-around normal pressure is applied to the sides of a cylindrical sample, corresponding to σ_3, and an additional axial pressure is applied along the axis of the specimen. Equilibrium conditions require that normal and shearing stresses, σ and τ, act on any plane other than a principal plane. Summation of the forces produced by σ_1 and σ_3 in the horizontal and vertical directions gives the following expressions:

$$\sigma_3 \, ds \sin \alpha - \sigma \, ds \sin \alpha + \tau \, ds \cos \alpha = 0 \tag{2}$$

$$\sigma_1 \, ds \cos \alpha - \sigma \, ds \cos - \tau \, ds \sin \alpha = 0 \tag{3}$$

Solving for the stresses σ and τ acting on the plane A - B, as defined by its direction θ to the major principal plane, yields

$$\sigma = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3) \cos 2\theta \tag{4}$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3) \sin 2\theta \tag{5}$$

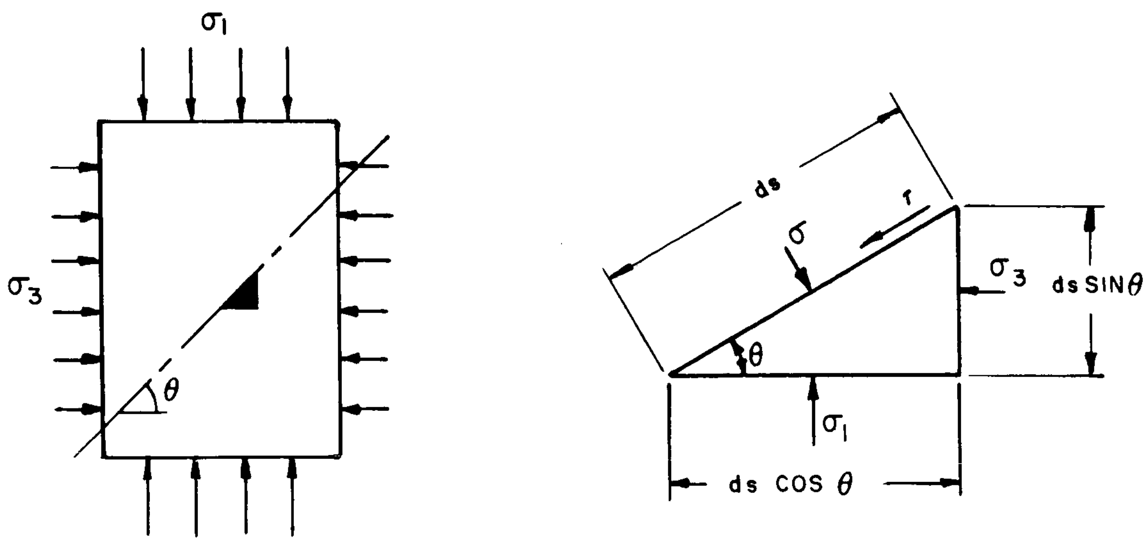

Figure III-2. Elemental Force System

A graphical solution of these equations is available through use of the Mohr diagram, Figure III-3. If normal stresses are plotted as abscissas and shearing stresses as ordinates on a rectangular coordinate system, all details that pertain to stress at a point may be shown by a circle. Since the shearing stresses on principal planes are zero, the principal stresses fall on the horizontal axis, at distances from the origin proportional to their magnitudes. The center of the circle falls on the horizontal axis at a distance $\frac{\sigma_1 + \sigma_3}{2}$; the circle diameter is equivalent to $\frac{\sigma_1 - \sigma_3}{2}$. If a radial line is laid off so that the angle A0'a is equal to 2θ, its intersection with the circle corresponds with values of τ and σ equal to those on the plane inclined an angle θ from the major principal plane, as defined by Equations (4) and (5).

It was previously noted that the shearing resistance of a soil mass is given by Coulomb's equation, (1), and it is assumed that the values of c and ϕ are independent of the states of stress which preceded the failure. This equation may be plotted as a line on the Mohr diagram, with an intercept, c, on the ordinate axis, where σ on the failure surface equals zero and an inclination angle ϕ to the abscissa axis. Any stress circle tangent to this line is a circle of rupture, since the coordinates of the tangent point represent the

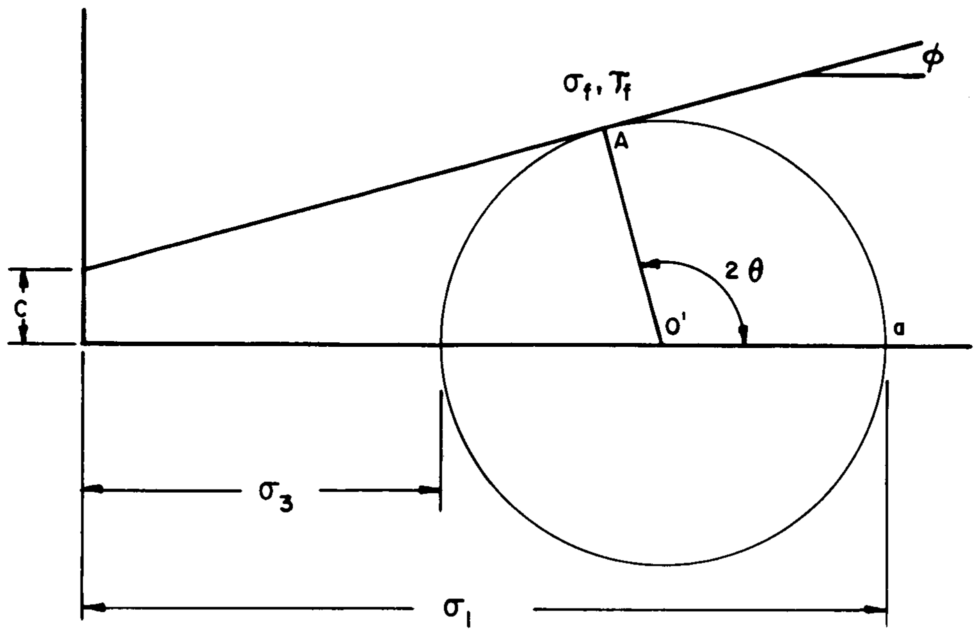

Figure III-3. Mohr Stress Diagram

stresses on a plane which have mobilized the maximum shearing resistance attainable under the existing stress conditions. Any stress circle below the line represents the locus of stress conditions at a point where the full shearing resistance of the soil has not been mobilized. Since points above the line correspond to stress conditions greater than maximum shearing resistance, any circle intersecting the line represents an impossible stress condition for the material in question. Also, according to previous definition of a plastic material, continuous deformation occurs at constant stress when the condition of rupture is attained.

The values of c and ϕ used in this analysis are independent of the state of stress, but they do vary according to the condition of the material. Lunar soils may exhibit high values of cohesive strength relative to the component of strength expressed by the term σ tan ϕ because of the effect of reduced gravity on the term σ and high particle bonding stresses. It is probable that the Mohr failure theory and the concept of plastic failure will be applicable to lunar soils, but there is no basis for predicting the shape of the failure envelope or the value of the shear strength parameters until the theory is validated in the moon's environment.

b. Bearing Capacity

Bearing capacity is not strictly a property of the soil, since it depends on the dimensions and depth of the loaded area as well as soil strength. However, the characteristic failure mode is dependent on the relative packing density of the material. When a load is applied to the soil through an area of limited dimensions, the surface settles. The relation between the unit load and corresponding settlement is shown by a settlement curve, Figure III-4, If the soil is fairly dense, the curve may show a well defined break at which excessive settlement occurs without a corresponding increase in load. This is called a general shear failure. Loose materials, on the other hand, may have load-settlement curves in which no distinct break is evident but in which the curve steepens progressively and approaches a tangent; such a condition is called a local shear failure. In such a case, bearing capacity may be given some arbitrary definition, such as the load which produces a given settlement, or taken as the abscissa of the point at which the curve becomes steep and straight.

Approximate theoretical methods exist for computing the bearing capacity of continuous footings and are described in soil mechanics textbooks. For footings with simple geometric shapes, such as squares and circles, not even an approximate theory is available. However, semi-empirical equations have been derived on the basis of experimental load tests (Terzaghi, 1943).

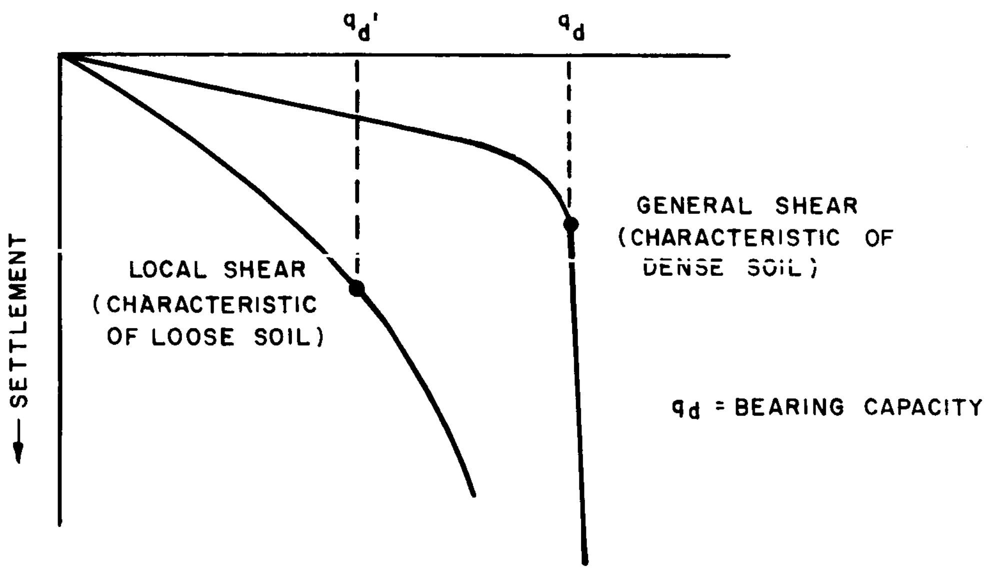

Figure III-4. Characteristic Load-Settlement Curves for Loose and Dense Soils

An approximate semi-empirical expression for the bearing capacity of a circular plate of radius R at a depth D below the ground surface of a fairly dense or stiff soil is

$$P = \pi R^2 \left[1.3\, c\, N_c + \gamma\, D_f N_q + 0.6\, R\, N_\gamma\right] \qquad (6)$$

in which the symbols N_c, N_q and N_γ are dimensionless parameters which depend on the value ϕ, and c is the cohesion term in Coulomb's formula. The "N" coefficients are determined from geometric constructions based on the theory of passive earth pressure against rough contact faces in which the controlling factor is ϕ; a chart for these coefficients is shown in Figure III-5. When the conditions pertaining to a local shear failure apply, it is customary to assume that the cohesion and friction of the soil are equal to 2/3 of the corresponding values given by Coulomb's equation, so that $c' = 2/3\ c$, $\tan \phi' = 2/3 \tan \phi$. The curves for bearing capacity factors N'_c, N'_q and N'_γ are used in this case. These arbitrary distinctions between general and local shear failure conditions by no means cover all possible conditions, but they have generally served as satisfactory, conservative approximations for practical design procedures.

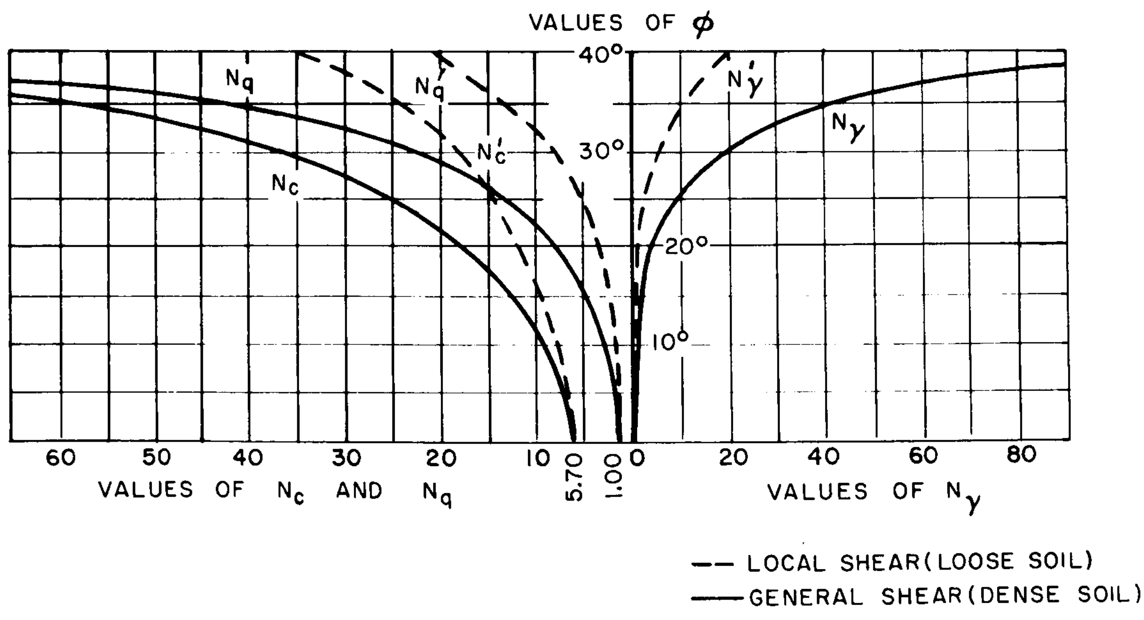

Figure III-5. N-Coefficients for Theoretical Computation of Bearing Strength (After Terzaghi, 1943)

c. Compressibility

Compressibility is the volume change occurring in a laterally confined soil due to application of a normal load. From a practical standpoint, in terrestrial soils this is principally important in fine-grained soft clays, where the normal stress displaces the pore water and the volume change in the sample is proportional to that of the drained water.

The compressibility of crushed minerals such as sand and mica mixtures has been studied principally as an academic subject. Volume changes take place rapidly in sands and coarse-textured materials as construction loads are applied and are usually small. An exception to this generalization is the case wherein repeated vibratory loads are applied to a loose granular subgrade.

Curves showing the volume change with increasing load are shown in Figure III-6. It is apparent that the presence of scale-shaped or platy particles greatly influences compressibility, and that the curve for a dense sand is considerably flatter than that for the same material in a loose state.

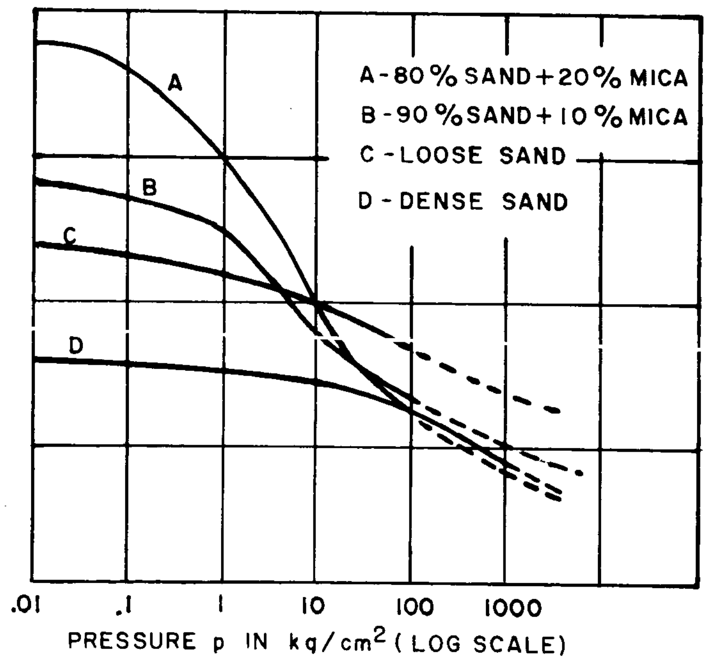

Figure III-6. Load-Settlement Relationships for Sand and Sand-Mica Mixtures (After Terzaghi and Peck, 1948)

Compressibility of sands and crushed minerals is the result of elastic deformation, slippage along intergranular points of contact, and at pressures exceeding about 100 kg/cm^2, crushing of mineral grains. The portion of the volume change due to elastic deformation can be observed, when the load is removed, by a decompression curve and hysteresis loop. The compressibility of lunar soils may be more important that that of terrestrial nonplastic soils because of the exceedingly porous structure anticipated. If a fibrous "reindeer moss" or "whisker" structure prevails, compression may occur as the result of breaking of individual fibers and subsequent densification as well as elastic deformation. A local shear failure occurring in a weak, porous lunar soil would be expected to compress the material in the zone of failure.

d. Compaction

It is necessary to redefine this phenomenon, since in terrestrial engineering practice compaction refers to a condition of density achieved with a specific amount of mechanical effort at a given water content. However, the relationship described below may be an important factor in lunar earthwork construction.

On the moon, it seems certain at the present state of knowledge that mechanical means will be needed for decreasing porosity and increasing the density of lunar soil construction materials. Ryan (1961b) discussed the nature of atomic bonds between soil particles and stated that increase of normal pressure, with accompanying increase in the area of real contact between particles, will increase the coefficient of mechanical friction. Certainly application of compactive effort and moving of soil particles closer together will introduce a wedging effect between these particles with consequent interlocking of the grain structure. This effect, coupled with the increase in surface contact and enhanced effectiveness of surface bonding forces, will impart considerable strength to such a soil.

A mold and drop hammer similar to those used in laboratory compaction tests may be used to test this concept. The compaction mold and tamper from the Harvard Miniature Compaction Apparatus are ideal for lunar use. The resulting compaction curve, showing densification as a function of blow count (a measure of compactive energy), may provide useful data for lunar earthwork design. Such an experiment could possibly be performed in a terrestrial vacuum chamber on a sample of lunar material, provided no contamination by the earth's atmosphere occurred.

E. EVALUATION OF TESTS AND MEASUREMENTS

1. General Discussion

Observations of properties and phenomena which can be made without apparatus other than a simple staff, and which contribute to general background knowledge of soils rather than specific problem areas, were discussed in Section D. Discussion in this section deals with measurements and related equipment in the soil mechanics category with reference to four pertinent, specific problem areas. No soil mechanics tests or measurements were identified that contribute directly to understanding the origin of the earth-moon system.

The list of Selected Measurements, Appendix E, includes measurements and equipment chosen for lunar operations under primitive conditions anticipated for the initial series of flights. These are essentially in situ experiments and tests; exceptions are the direct shear and compaction experiments which may be performed on disturbed materials. Observation of soil horizons or layers can be noted either in exposed cuts made by a hand tool or on soil cores.

The list of measurements does not include various tests and experiments which can be performed most feasibly on samples in a laboratory. This is not intended to downgrade the importance of such tests as triaxial, shear, compression, etc., but serves to indicate that the weight and complexity of apparatus required, time constraints or other factors mitigate against selection of such equipment for early APOLLO missions.

It is recommended as a general guide that every object placed on the lunar surface, every type of disturbance and every unique feature of lunar soil and topography be photographed, preferably stereoscopically and in color. Even such mundane features as footprints and the imprints of packages placed and removed from the surface can yield information on bearing strength and behavior of lunar soils which is possibly more useful from a practical standpoint than a highly precise measurement of force transmitted through a 2-in. diameter bearing plate.

2. Hazards

When an APOLLO astronaut goes out on the lunar surface, he will already have ascertained from the LEM descent and pre-egress safety procedures that there is sufficient bearing strength to support the LEM, and that the surface is non-reactive. Since the environment may appear totally strange and hostile, each step of the way must be accompanied by a careful test of the ground immediately in his path and a continuing re-evaluation of possible hazards. For such a process, no instrument is likely to be as valuable to this first explorer as his own powers of observation and judgment. However, two simple instruments might be used to supplement his judgment. The first, called a "tethered sphere," is conceived as a spherical mass on a string which can be cast a few feet ahead of the astronaut and retrieved by winding in the string. It can be designed conservatively so that soil bearing strength adequate to prevent its excessive sinkage into the soil will be roughly equivalent to that required to sustain the astronaut's weight. This will enable the astronaut to test hazardous terrain, especially deep deposits of low density, without venturing close enough to jeopardize his safety. The second instrument will be a simple probe or staff for testing the ground closer at hand to determine whether the existing crust will withstand the astronaut's weight and to test subsurface consistency. After a few steps he should be able to evaluate the ground on a qualitative go or no-go basis by the probe reaction.

Penetration resistance, as a mechanical property of soils, embodies a number of factors which can be empirically correlated by means of quantitative measurements such as bearing capacity and shear strength. A proving ring or similar device attached to the staff to make penetrometer measurements may not be necessary until after several APOLLO flights have occurred.

In the event that surface materials prove to be too weak to sustain the astronaut's weight, the next most important question would be: "How deep is the weak layer?" If surface materials are shallow, the weak materials would compact under load through a local shear failure, and sinkage would not immobilize him. Depth, up to the limit of the probe, can be easily investigated. Probing would also reveal dust-covered fissures, indicate the strength of surface cohesive forces in bonded structures and aid in evaluating differences in soil structure from place to place which may be indicative of hazardous conditions.

The possibility that dust particles may adhere to the astronaut's space suit and thus immobilize him is considered remote though present. Such a phenomenon may be apparent as soon as the first object is lowered from the LEM to the lunar surface and retrieved. On the other hand, dust particles may be a local hazard related to lateral variations in soil. A lightweight coverall may be worn over other clothing which could be shed if it became dust laden. When this occurs, the investigator should return to the LEM by the same path taken in the outbound excursion.

Bearing strength is an important variable for evaluating possible terrain hazards, and criteria should be developed at an early stage for its measurement in anticipation of later missions with greater payloads and extended ranges. When impassable or near-critical conditions are encountered, they should be tested for an indication of the range of conditions which future missions must be prepared to negotiate. This will be discussed in greater detail in connection with trafficability.

Criteria for field classification of lunar soils must be found which indicate hazardous conditions, if present. Initially, however, intuition and judgment of lunar explorers must suffice, since present knowledge is inadequate to predict surface conditions. The most important tool for this purpose will be the camera, since a film record of any visible hazard or index property which indicates impassable terrain, will be invaluable for terrain evaluation and training of future exploration teams. Factors indicative of hazardous conditions could be soil structure, grain size and topographic position as discussed in a previous section. If the Gold hypothesis is correct, deepest dust deposits will accumulate in depressions and the maria. Depth, however, may not be the only criterion of hazardous conditions; dust deposits characterized by low cohesion and lack of frictional strength on steep slopes could present significant danger because of the sliding hazard. Landslide potential is largely a function of shear strength, and the stability of an earth mass can be evaluated for several different modes of failure if the geometry and shear strength parameters are known. Rockfalls may constitute a significantly greater hazard in mountainous areas, and these are not subject to any practical theoretical analysis. This would not seem to be of concern in early APOLLO landings, since mountainous landing sites would present formidable navigation hazards and mission time constraints probably will not permit extended sorties from the spacecraft.

3. Trafficability

Many of the conditions and soil properties pertinent to trafficability are the same as those for hazards. Any terrain which cannot be negotiated by available means of locomotion constitutes a hazard. However, the terms used are principally in the context of pedestrian vs vehicle trafficability.

The trafficability problem has a dual nature. First, measurements are needed to establish soil and terrain-dependent criteria for predicting the performance of vehicles with established design characteristics in the environments encountered. This involves two main tasks: a) determining by empirical means the limiting conditions for support and locomotion of specific vehicles, and b) ascertaining, by representative field measurements and mapping, areas in which common limiting ranges of these conditions exist. These tasks can be accomplished most expeditiously by testing, with a penetrometer, the limiting ground conditions for operation of a given vehicle. Such testing will establish a "vehicle cone index" value, corresponding to the minimum soil strength required to operate the vehicle under specified conditions. Any terrain which, when subsequently tested in the same manner, has a cone index rating equal to or greater than the vehicle cone index is presumed strong enough to support the vehicle in question.

The second aspect of the trafficability problem, usually called the mobility problem, refers to the matter of measuring terrain parameters which can be translated into vehicle design specifications. The best known technology in this field is the Bekker system of land locomotion mechanics. In this system, independent observations for bearing capacity and shear strength are made and used to compute soil mobility parameters which can be translated into vehicle design specifications according to Bekker's theory. The lunar bevameter developed by General Motors Defense Research Laboratory for the Surveyor soil mechanics experiment appears to fully satisfy the data requirements for the Bekker system. In addition, the device fulfills the requirement for a research instrument which can be used to investigate the nature of soil action on the moon including shear strength-evaluation of the ϕ and c parameters in the Coulomb equation and bearing capacity experiments concerned with the forms of load-settlement curves and critical load values. The principal limitation of this instrument for use on the moon is the need to provide some sort of load and torque reaction. Thorman (1963) notes that on a spacecraft having terrestrial weight of 600 lb or a lunar weight of 100 lb, contemplated use of this instrument as the reactive mass would limit axial load for any of the test devices to 50 lb to avoid lifting the spacecraft. Since the smaller penetration plate has a diameter of 2 in., the maximum measurable bearing strength will be about 15 psi. Such a restriction may be acceptable for purposes of vehicle design but may be too stringent for evaluation of general soil behavoir or development of design criteria for lunar bases. It is desirable in such cases to load the soil to failure. If the bearing strength is greater, this test could be performed by using smaller penetrometer pads, but there would seem to be a limit imposed by the soil structure and texture on the minimum-size loaded area that will yield a valid, representative test. Use of the LEM as a reaction would permit testing of an exceedingly limited area whose conditions may be altered by the descent blast. Sufficient reaction may be possible by the use of screw augers which could be turned into the ground.

Use of the apparatus discussed above may not be feasible until payload constraints permit some sort of cart or roving vehicle on which the device can be mounted. On the other hand, if the soil has sufficient strength, a base plate with screw anchors may provide a suitable reaction. Also, there is the possibility (Trafficability Research Team, 1961) of empirically relating cone penetrometer valves to the Bekker mobility parameters. Another experimental instrument, the soil truss (Harroun, 1953), was developed for trafficability studies. As with the cone penetrometer, reproducibility of results is somewhat dependent on operator skill.

Ratings in the trafficability category were assigned with these factors in mind. Excessive sinkage is apt to be the principal cause of immobilization; hence, the highest rating assigned was that of bearing strength. Penetration resistance would give a valid indication of bearing strength in cohesive materials, but for heavier traffic loads an observer might lack the ability to interpret penetration behavior intuitively. The trafficability system based on penetrometer measurements as developed by the U. S. Army Engineer Waterways Experiment Station is applicable mainly to cohesive soils and has not been extended to those soils which develop their strength principally from intergranular friction. On the other hand, the Bekker system is applicable in either case and provides design data which can be used effectively by vehicle manufacturers.

Soil depth is second in importance among the tests in the trafficability category. This is important principally because even in weak soils a vehicle could operate effectively if the depth to firmer material was shallow--provided that rolling resistance was not too great. It is expected that sinkage would be accompanied by compaction in the material immediately below a vehicle gear, which would in turn increase the shearing strength and bearing capacity of the soil.

Since bearing strength is largely a function of shearing strength, it follows that when bearing strength is adequate to support a vehicle, shearing strength will not be a critical factor. It may, however, limit the thrust which can be developed between the soil and vehicle gear, and is thus a consideration in acceleration and climbing ability of a locomotion system. For this reason, and because of its essential role in design analysis, shearing strength is included in the list of desirable measurements.

Other significant factors within the scope of trafficability are color and bulk density. These were accorded relatively low ratings, but were included because of their possible use as index factors in field classifications which might relate to the trafficability properties of soils. This was already discussed with respect to hazards. Bulk density has a major influence on bearing strength, shear strength and penetration resistance, but presumably it would not be measured when the latter properties can be measured directly with much greater ease.

4. Lunar Basing

The science and technology of soil mechanics grew out of a need for analytical tools and measurements to cope with problems arising in earthwork, embankment and foundation construction. It is in this context that most progress has taken place. Presumably, many construction techniques and problems encountered on earth will be applicable to the moon. Among these are problems relating to slope stability, settlement, footing design, excavation, earth pressures on walls, cribs, conduits, compaction, and transportation. The hydraulic phenomena which play a major role in the engineering behavior of terrestrial soils and dictate many unique construction features for control of seepage are not anticipated in the lunar environment. This supposition automatically makes much available knowledge of terrestrial soil behavior irrelevant, but other factors, such as the surface forces manifested by soil particles, may assume greatly enhanced significance.

Questions which require immediate answers to harden lunar basing concepts are easily identified. Foremost among these is the need for an accurate description of the lunar soil with respect to its depth, structure, possible texture, and bulk density. Large scale photographs taken on the lunar surface and photomicrographs of samples returned to earth will advance knowledge of structure and texture immeasurably. The bulk density of undisturbed samples can possibly be estimated from the photographs but should be determined by direct measurement of the hole volume from which the sample was extracted, in combination with the sample weight. A thin-walled sample tube thrust into the soil a known distance will suffice to determine the volume if the density is sufficiently low and soil bonds are weak.

Next in importance is an evaluation of the range of soil depths which may exist within the limits of the region selected for reconnaissance. For planning purposes, generalizations for large portions of the lunar surface can probably be made by sounding four or five locations, at various topographic positions, within 1000 ft of the LEM. As previously noted, depth of soil may be a severely limiting factor in selection of a site for base development because of the desirability of having adequate sources of material for borrow and emplacement of subsurface facilities. Blasting and crushing as an alternative may be extremely hazardous in the lunar environment.

Assessment of soil depths on a regional basis is closely tied to the matter of soil classification and mapping and should be considered in the same context. Areal differences in soil deposits, including depth, invariably affect the design and performance of engineering works and should accordingly be identified as a matter of course in any base reconnaissance. During early missions, hand probing and boring will provide data concerning soil depth. Eventually, it may be feasible to measure continuous soil depth profiles electronically. Green (1963) has discussed an investigation into feasibility of a sonic velocity system for measurement of dust depth.

Selection of a lunar base location may be controlled by many factors; foremost among them is certain to be soil. Since permanent base construction will not be initiated until 3 to 4 years after the first landings, and only rudimentary construction capability is needed to support APOLLO landings (Corps of Engineers, 1963), detailed tests and investigations at selected sites should be deferred until general reconnaissance has established the ranges and variations in soil properties and terrain. During this period, however, general investigations into the nature of lunar soil action must be undertaken to verify the concepts discussed previously, i.e., bearing capacity failure modes, shapes of load-settlement curves and shapes and parameters of Mohr strength envelopes.

Since lunar soil and rock will be the only indigenous construction materials available, it is important to determine ranges of compaction properties and note special problems which may be encountered in excavation and placement. For measurement of compaction, a compaction cylinder, manual drop hammer and laboratory scale will suffice. The intended objective of this test is determination of the density vs compactive effort relationship. The compacted samples should also be subjected to a penetration test, such as the laboratory CBR test, to measure the modulus of deformation at various compacted densities. Development and transportation of a lunar testing machine would be necessary for this purpose; as a field substitute, the Proctor penetrometer may suffice.

The penetrometer pads on the Surveyor soil mechanics apparatus are probably adequate for mobility measurements and general field investigations. However, in connection with site evaluations, at least one load-bearing test using a larger plate should be performed. The test apparatus, probably mounted on a roving vehicle, should be capable of delivering a load to the plate equivalent to twice the anticipated design unit stress or to the failure strength of the soil. This may limit the size of the plate. In connection with this and other tests, there is a need for terrestrially based experimental evaluation of the influence of small discontinuities in soil, such as voids, cracks, and pebbles in fine-grained soil, on test results obtained with apparatus of various sizes. Considerable effort will be devoted to miniaturization of test apparatus, and should be preceded by experiments to determine the effects of such factors and scaling. An example of miniaturized test equipment which has performed successfully in selected soils is the Harvard miniature compaction system.

Virtually every soil design computation involves the shear strength parameters ϕ and C, hence their evaluation is a necessary basing measurement. It is also essential for the soil mechanics specialist to know the shape and limits of the load-deformation curve. Evaluation of shear strength by lunar laboratory direct shear apparatus is recommended. Commercially available test equipment is too heavy and bulky for lunar shipment, but test apparatus similar to that used at Illinois Institute of Technology (Vey and Nelson, 1963) in vacuum chamber experiments can possibly be modified for use on the moon.

Direct shear tests should be supplemented by field vane shear tests to evaluate soil deposits in situ. Also, the Mark II soil truss is applicable to lunar shear strength measurements in place, provided the materials encountered are not so weak that the applied normal load causes sinkage. This instrument reportedly reproduces laboratory direct shear test results very well in sands, but produces variable cohesion values in plastic soils, depending on the rate of strain. This effect may not be severe enough to cause concern in lunar soils, provided they behave like cohesionless terrestrial materials.

Simulation of lunar phenomena in terrestrial vacuum chambers is expected to continue for many years after man has reached the moon. This is because the high cost of transporting materials to and from the moon dictates that all equipment and design concepts be checked out carefully before prototypes are launched. Since a major parameter of any environmental model is the soil, it is necessary for the simulated soil to behave as much like its prototype as possible. The mechanical behavior can be tested by transporting a small amount to the moon and performing tests, such as shearing strength and bearing capacity, in the moon's environment. A correspondence between the behavior of the lunar soil and the simulated soil would be very convincing evidence of similitude.

5. Origin, History and Age of the Lunar Surface

Science advances through observation of natural phenomena, development of hypotheses and subsequent investigation in controlled experiments. The earth environment, notably the hydrosphere, obscures a great many phenomena of interest in soils and so complicates matters that separation or control of the variables which affect soil behavior is extremely difficult. A good example is the presence of adsorbed gas, especially water vapor, on the surface of all mineral particles which have been exposed to the atmosphere for even a few minutes during their "lifetime." In the absence of a hydrosphere on the moon, it may be possible to study the influence of interparticle forces on soil strength and the phenomenon of mechanical friction far more effectively than on earth.

Virtually every question raised about lunar soils assumes the stature of a major scientific problem at the present state of knowledge. Obtaining the most trivial data presents overwhelming problems of measurement and observation.

Hypotheses regarding the soil structure -- whether it be "cotton candy," "fairy castles," "reindeer moss," or "whiskers" -- can be largely solved by visual examination. Measurement of particle bond strength, perhaps as a function of cohesive strength (shearing strength at zero normal stress) will yield useful information concerning the source of surface forces which support these structures. Sputtered structures and metallic enrichment of the soil should be fairly easy to recognize by characteristic structure, brittle fracture of a surface crust and mineralogy. Lapilli, glass shards and lava structures would indicate distinctive origins.

Mechanisms of soil formation, such as the sputtering phenomenon, condensation of vaporized materials produced by meteoritic impact and thermal fracturing (Weil, 1961), may be difficult to observe directly. Unique grain shapes may provide clues relating materials to respective theories of origin; the thermal fracturing theory may be supported by gradation of particles, which should tend to be fairly course, and evidence of rock spalls or hairline cracking in exposed rock surfaces.

Evidence of operative transportation mechanisms will be obtained from distribution of materials between topographic highs and lows.

Radiation damage, as a soil-forming process, may be evident from so-called "metamict"[1] structure in rocks. A general deterioration of the "intrinsic stress," which gives rise to tensile strength in solid bodies may be manifested without destruction of external form.

Mineralogy of lunar soils may reflect their mode of origin and may possibly affect their mechanical properties. At the particle size range predicted by most investigators, about 10 microns, X-ray diffraction techniques would be most useful for these measurements. These tests could be carried out on earth with ease, provided the samples were sealed to prevent atmospheric contamination. In connection with such analyses, it would be desirable to detect presence of adsorbed or chemisorbed gas layers on the particle surfaces. Differential thermal analysis of samples with gas chromatographic analysis of thermal decomposition products could be used to detect and measure these gases.

Any visual evidence of soil layering would indicate variations in the intensity of soil-forming processes or environmental factors. Some of these might include stages of volcanism, major meteoritic impacts or changes in the intensity of the solar wind and the radiation phenomena.

F. CONCLUDING REMARKS

It is apparent from evaluation of the foregoing measurements and equipment that considerable development effort is needed to produce soil mechanics hardware suitable for early APOLLO missions. The recommended tests are primarily those which measure soil properties in place. Initially, test results on returned samples will advance knowledge of lunar materials and their mechanical properties by orders of magnitude. Even so, there is much to be said for performing laboratory tests such as direct and triaxial shear, compressibility, compaction, and CBR on the lunar surface in order to realize the full range of environmental factors which could possibly affect test results. Obvious reasons are: a) greater statistical reliability can be achieved through testing more samples; b) structural disturbance of samples will be minimized; c) the risk of atmospheric contamination will be minimized; and d) problems of similitude, involving dimensional relationships between mass, length, time, and other factors are circumvented.

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1. Ryan (1961b), discussing radiation as a soil-forming process, defines metamict minerals as those which have lost all vestiges of crystal structure through long-period exposure to natural radioactivity.

Development of instruments for these measurements will require considerable ingenuity and knowledge, beyond that which now exists, of scale effects and inhomogeneities in soil. In principle, test results average the effects of discrete particle size, shape and structural arrangement in the same manner as nature. However, when test equipment is miniaturized, fewer soil particles make up the sample, and the relative effect of each is proportionately greater. Thus experimental evaluation of these factors should be performed to establish specifications for miniaturized instruments and tests which do not compromise test objectives.

An effort should be made to standardize parts of sampling and testing apparatus such as power supplies, gear trains, proving rings, dials, sample holders, sample tubes, and any other components, so that weight and handling is minimized. Unique means must be found to apply constant loads to samples during testing, independent of strain, to eliminate weights and hangers as well as elaborate hydraulic systems such as those used in conventional laboratory testing machines.

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CHAPTER IV

SUPPORT TECHNOLOGIES

A. SUMMARY

Surveying, mapping, photography, and sampling are activities required by most disciplines to insure retrieval of maximum information from the moon. Two of these activities, photography and mapping, were given the most emphasis in letters received from the scientific community (see Appendix A).

Samples are necessary to the lunar geologists for age determinations, chemical analyses and for mineralogical studies. Geophysists will use them to measure density, velocity, resistivity, and magnetic susceptibility. Soils engineers need samples to measure parameters bearing on trafficability and basing.

Photography will help record geological and engineering details at sample sites since the astronaut may not have time or specialized training to describe such details to the satisfaction of earth-based experts. It will also be used to simplify the recording of many surveying and mapping details.

Surveying and mapping will help relate the LEM landing-site information to remote sensor data (e.g., infrared and radar imagery and visible photography) as an aid in extrapolation of point data over relatively large areas.

Essential sampling equipment consists of relatively simple tools such as a hammer, pick, rock saw, and sample containers. Since later missions may require power tools and other more complicated devices, design of power tools and ultravacuum-tight containers could be a major task and warrants immediate investigation.

Photographic mapping and surveying techniques will use the LEM TV to track the roving astronaut and to determine his bearing from the LEM. In addition, some of the LEM-astronaut communication electronics will be employed with the TV to monitor the astronaut's distance from the LEM. Additional required equipment will consist of a descent camera for recording the position of the landing site; a hand stereo camera to record background and survey data at sample sites; a gyro and possibly a sun compass to obtain azimuth data; an inclinometer for measuring dips; and a tape recorder to note the astronaut's technical comments.

Much progress has been made on designing space and TV cameras, but little work has been done to adapt them to lunar surveying and mapping purposes. Testing and evaluation of recommended equipment and techniques under space suit conditions are urgently needed.

B. SAMPLING TECHNIQUES AND INSTRUMENTATION FOR LUNAR EXPLORATION

1. Introduction

Terrestrial sampling methods have been studied to determine their possible application to lunar surface exploration. Basic problems include acquisition of samples which will yield the most significant data and their packaging to preserve mechanical and chemical integrity during the return trip.

Initial efforts were directed toward listing surface and shallow-subsurface sampling techniques and subsequently determining which of these would yield the greatest amount of significant data. Successful completion of such work depends upon a thorough understanding of sample types required for maximum data return. This reasoning dictated dividing the study into three phases:

PHASE I - Sampling Specifications

PHASE II - Sampling Techniques and Instrumentation

PHASE III - Recommended Sampling Equipment and Procedures

These phases were further subdivided to provide a simplified study outline (Table IV-1) as an objective guide to synthesize the information into conclusions and recommendations.

TABLE IV-1

OUTLINE FOR LUNAR SAMPLING STUDIES

PHASE I SAMPLE SPECIFICATIONS	a. Definition of samples b. Sample requirements related to tests and properties to be studied
PHASE II SAMPLING TECHNIQUES AND INSTRUMENTATION	a. Sampling methods and techniques b. Instrumentation survey and evaluation c. Recent investigations

TABLE IV-1 (CONTD)

OUTLINE FOR LUNAR SAMPLING STUDIES

PHASE III RECOMMENDED SAMPLING EQUIPMENT AND PROCEDURES	a. Rating system for sampling equipment b. Preference rating, weight, and volume of sampling equipment c. Recommendations and modifications for simple tools d. Recommendations and modifications for complex (powered) tools e. Recommendations for sample containers

2. PHASE 1 -- Sample Specifications

a. Definition of "Samples"

Definitions used in this study were adopted and modified from Hvorslev(1949). These were not originally intended to be used in hard rock sampling; however, it is felt that they do apply since the tests and property studies are essentially the same whether the sample is consolidated or unconsolidated. Accordingly, samples may be classified as to the condition or disturbance of the sample material as follows:

(NR) - Non-Representative samples consist of a mixture of materials from various soil or rock layers, or they are samples from which some mineral constituents have been removed or exchanged, thus destroying the mechanical integrity during the sampling process. (LOSS OF BOTH MECHANICAL AND CHEMICAL INTEGRITY)

(R) - Representative samples contain all the mineral constituents of the intervals from which they are taken and have not been contaminated from other intervals or by chemical changes during the sampling process; however, the soil structure is seriously disturbed and the gas or fluid content may be changed. (LOSS OF MECHANICAL INTEGRITY -- CHEMICAL INTEGRITY PRESERVED)

(U) - Undisturbed samples may be defined broadly as samples in which the material has been subjected to so little disturbance that it is suitable for all laboratory tests and thereby for approximate determination of the strength, consolidation, permeability characteristics and other physical properties of the material in situ. (BOTH MECHANICAL AND CHEMICAL INTEGRITY PRESERVED)

If a uniform material covers the lunar surface, areally and vertically, non-representative samples could not exist as defined. The primary distinction between representative and non-representative samples is dependent on the occurrence of compositional and textural changes. A representative sample within some given vertical or horizontal interval is a non-representative sample for any smaller interval within that range, assuming that the sampled area is not homogeneous.

b. Sample Requirements Related to Tests and Properties to be Studied

Table IV-2 shows the relationship between the "tests and properties to be studied" and the required types of samples. It is apparent such information must be carefully considered before conducting any protracted study of lunar instrumentation and sampling techniques. These test and property studies are grouped by scientific disciplines to relate the needs of various program study groups to a specific "type" sample of minimum size, shape and mass.

The sample type, indicated in the first column, is not merely a preference but an actual need for fulfillment of total test requirements of each study group. Non-representative samples do not meet the total requirements of a single study group; whereas, representative samples yield only a small amount of data when compared to an undisturbed sample. Based on indicated needs, the primary objective of the sampling group should be the acquisition or development of a sampling tool capable of obtaining relatively undisturbed samples with a minimum expenditure of time and energy.

Shape and size of samples are based on composite minimum needs of the study groups and are indicated in Table IV-2. An analysis of group needs indicates that the relative desirability of various sample types is as follows:

TABLE IV-2

REQUISITE SAMPLE INFORMATION RELATED TO TEST AND PROPERTY STUDIES

TESTS AND PROPERTIES	TYPE SAMPLE * Unconsol.	TYPE SAMPLE * Consolid.	SAMPLE SHAPE AND SIZE (inches)	SAMPLE MASS* (lb)	TYPE TESTS	REMARKS
1 Rheologic and soil mechanics properties	R U	U	R - Unconsolidated bulk samples 2.3 x 2.3 x 4 U - Unconsolidated and consolidated, 3 x 6. cylindrical	R = 15 laterally spaced bulk samples-unconsolidated - 5.8 - 23.0 U = 1 each- Unconsolidated-0.9--3.3; Consolidated - 3.3--8.0	Tests are mechanically destructive; sample is chemically unaltered.	
2 Geology	U	U	U - 0.8 x 4.3 cylinders of consolidated and unconsolidated material	15 - Unconsolidated samples 0.7 - 2.4 15 - Consolidated samples 2.4 - 6.0	Tests non-destructive; very small amount needed for thin sections.	Also meteoroid, paleontological and biological samples.
3 Composition and age	R U	R U	R - Same as #1 U - Same as #2	Use samples from #1 Use samples from #2	Tests partially destructive mechanically and chemically -- less than 10 per cent.	
4 Geophysics	U	U	U - 3 x 6 cylinders - same as #1 U - 0.8 x 4.3 core - same as #2 U - 2.3 x 2.3 x 4 rectangular samples	Use samples from #1 Use samples from #2 3 unconsolidated - 1.0 -- 4.8 3 consolidated - 4.8 -- 11.0	Tests non-destructive	Separate sample with non-metallic sampler. Rectangular samples for paleo-magnetic studies
5 Reflectivity and emissivity	U	U	U - 2 x 12 x 12 square-consolidated U - 2 x 12 x 12 square-unconsolidated	1 - sample - 20.7 -- 52.0 1 - sample - 5.2 -- 20.7	Tests non-destructive	Requires large sample -- make tests on lunar surface
6 Erosion, transport and deposition rate	R		Depositional residue or trapped particulate matter.	Dependent on conditions and time factor.	Tests non-destructive	Counting and mechanical studies
7 Gases	R		Container shape	Mass of getters	Destructive	
Conclusions	<u>Sample Preference</u> 1 - U 2 - R 3 - NR		<u>Shape and Size Preference</u> 1 - U -- 0.8 x 4.3 cores 2 - U -- 3 x 6 cores 3 - R -- 2.3 x 2.3 x 4 bulk 4 - U -- 2.3 x 2.3 x 4 blocks 5 - U -- 2 x 12 x 12 squares	<u>Total Mass**(lb)</u> Min. / Max. Excluding #5: 19.0 / 59.0 Including #5: 44.8 / 131.0	<u>OPTIMUM TEST SEQUENCE</u> 1. Non-destructive 2. Mechanically destructive 3. Chemically destructive 4. Mechanically and chemically destructive	Total mass does not include any meteoroids, paleo or biological samples

* U -- Both mechanical and chemical integrity preserved
R -- Loss of mechanical integrity -- chemical integrity preserved
NR -- Loss of both mechanical and chemical integrity

**Postulated density -- lbs/in^3

	Min.	Max.
Unconsolidated --	0.018	0.072
Consolidated --	0.072	0.180

- <u>Undisturbed</u> - Cores 0.8 x 4.3 in., consolidated and unconsolidated material; or the equivalent, such as blocks or pieces obtained by hammering, sawing and cutting.

- <u>Undisturbed</u> - Cores 3 x 6 in., consolidated and unconsolidated material; or the equivalent, such as blocks or pieces obtained by hammering, sawing and cutting.

- <u>Representative</u> - Bulk 2.3 x 2.3 x 4 in., consolidated and unconsolidated material. Large fragments (exceeding 1 $in.^3$) may be considered undisturbed samples.

- <u>Undisturbed</u> - Rectangular 2.3 x 2.3 x 4 in., consolidated and unconsolidated material

- <u>Undisturbed</u> - Square 2 x 12 x 12 in., consolidated and unconsolidated material

- <u>Non-representative</u> - Bulk 2.3 x 2.3 x 2.3 in., consolidated and unconsolidated material

Sample amounts needed by each group were related to the planned tests and properties to be studied with respect to the destructiveness of such investigations. Tests to be performed on each sample by the study groups were rated as to whether they were:

- Non-destructive
- Mechanically destructive
- Chemically destructive
- Mechanically and chemically destructive

The total number of samples was greatly reduced by assigning a priority to the testing procedures based on these factors; i.e., total requests for 0.8 x 4.8-in. consolidated cores exceeded 40 in number, but only 15 are required when testing priority is properly assigned.

Estimates of the density of the lunar surface material indicate that total sample requirements can be met within the limits of the alloted 80 lb (including containers, film and tape). These estimates do not include the large samples required for integrating purposes in the emissivity and reflectivity studies. Although these measurements probably can be carried out best on the lunar surface, methods to obtain the size sample required are an integral part of sampling studies.

3. PHASE II -- Sampling Techniques and Instrumentation

a. Sampling Methods and Techniques

More than 200 methods that could possibly apply to sample acquisition were compiled and classified by type. The list included such methods as boring, sawing, cutting, chiseling, and scooping.

b. Instrumentation Survey and Evaluation

Using the tabulated sample acquisition data as a guide, more than 500 "state-of-the-art" instruments, techniques and accessory items were reviewed. Of these, approximately 80 items were listed on engineering evaluation sheets (Appendix D).

The "type sample" column generated a gross scientific evaluation of sampling techniques since the quality or type of sample possible is a direct measure of the instruments' value in lunar exploration. The considerable overlap in sample types, when classified by instrument, is primarily a function of the manner in which the instrument is applied; i.e., chipping in a small area with a pick will yield a representative sample but when applied for the purpose of removing an "in place" block, an undisturbed sample can result.

Selection of instrumentation from the engineering evaluation sheets was based on the wide variety of possible sampling techniques deemed necessary. Techniques considered were as follows:

Hammer
Sawing
Cutting
Scooping
Boring
Grasping and holding
Magnetic attraction
Absorption and particle entrapment

Hammering, boring and sawing techniques were also considered from the standpoint of powered units which are discussed in Phase III. Any instrumentation package combining all of these techniques should insure acquisition of a suitable lunar sample regardless of the condition of the lunar surface.

c. Recent Investigations

A comprehensive literature search revealed only a limited amount of study for the evaluation and design of tools to obtain lunar samples. None of this effort was directed toward evaluating simple tools, although the need for simple tools is implied in most studies concerned with lunar exploration.

The most recent investigations (Armour Research Foundation, 1961: Hughes Tool Co., 1960: Texaco, Inc., 1961) yielded positive results for defining methods of drilling a hole on the lunar surface and acquiring broken media by mechanical removal from the hole. Primary aims of these investigations were to determine the following:

1) Which drilling method will bore an economical hole most efficiently in terms of time, weight, power, volume, reliability, and simplicity?

2) What type of sample can be obtained with this method and how can it be obtained concurrent with the boring process?

These investigations have been quite thorough concerning drilling and clearly show that the rotary-percussive method more nearly satisfies all requirements for making hole and mechanically obtaining samples of the broken media. Investigations of item 2 has been primarily concerned with obtaining a sample without ample thought being given to its scientific and technologic significance. The net result of these investigations has been the development of complex mechanisms which can bore a shallow hole for the insertion of measuring sondes and for the simultaneous acquisition of a non-representative sample. The present studies have shown that a non-representative sample can contribute only a relatively small amount of scientific and technologic data compared to undisturbed samples. Consequently,sampling studies should be directed toward obtaining undisturbed samples. The importance of the hole for making vertical measurements by the insertion of various probes is understood. However, the desirability of these vertical tests during the initial phases of lunar exploration must be explored more fully.

Investigations of penetration rates (Hughes Tool Co., 1960) would indicate that if some or all of the lunar surface is equivalent in hardness to Berea Sandstone (called a medium hard sandstone), adequate samples could be obtained by using a small battery-powered rotary drill with a masonry core bit or carbide-tipped hole saw. Their tests indicated a penetration rate of nearly 14 ft/hr @ 1000 rpm using a 1-7/8 in. diamond-tipped core bit with a 5/8 in.

finite cutting annulus. The bit load was 50 lb with a gas flow of 28 cfm for removing the cuttings. With half the load and a more suitable bit, no trouble is anticipated in obtaining a 5-in. core in a period of time of 5-10 min in material equivalent to Berea Sandstone.

These investigations also revealed that rotary drilling, under the same conditions, had a maximum penetration rate in gray granite of only 1 - 1/2 in. /hr. If material of this hardness were encountered, rotary drilling would be ineffective for sampling purposes. However, further investigations by Hughes indicated a percussive drilling rate in Harris granite (assumed to be about equivalent in hardness to the gray granite) of 11.5/ft/hr using a 1 in. chisel bit, a gas flow of 20 cfm, and a load of 65 psi. Under the same conditions the penetration rate in Berea Sandstone was 66 ft/hr. Using less load and a smaller bit under the same conditions, no difficulty is expected in extracting an "in place" block of hard material by hammering and chiseling a series of small holes and utilizing any existing small surface fissures.

4. PHASE III -- Recommended Sampling Instrumentation and Procedures

a. Rating System for Sampling Equipment

Tools selected from the engineering evaluation sheets satisfying techniques listed in Phase II-2b, were rated on the grading scale given in Table IV-3. All of the measurands were rated from 1 to 5 except the "type of sample acquired" which was weighted double because of the scientific and technologic significance attached to the acquisition of a proper sample. This rating resulted in a reasonably objective order of preference for the sampling tools and greatly reduced the number of items for consideration in Chapter V.

Table IV-4 is a rating chart of sampling instrumentation based on the mission suitability measurands listed in Table IV-3. A subjective review of this rating chart indicates a few minor adjustments are desirable for a more suitable order of preference for sampling tools. This subjective evaluation involves the following changes:

- A magnet should be considered an accessory item since its primary function is not the physical acquisition of a sample (forceps or scoops will do the same job) but the differentiation of similar appearing samples or outcrops. A magnet of less than 0.5 in.^{3} in volume and a few ounces in weight is recommended as an accessory item.

TABLE IV-3

RATING SCALE FOR MISSION SUITABILITY MEASURANDS

MISSION SUITABILITY MEASURAND

(1) RELIABILITY	RATING	HAZARDS - ACTIVE STATE (2)
Very reliable	1	Activation involves no hazards
Reliable	2	Activation may involve hazards
Fairly reliable	3	Activation will involve hazards
Poor	4	Activation will involve hazards even with shielding
Unreliable	5	Activation implies extreme danger

(3) SETUP TIME	RATING	OPERATING TIME (4)
0 - 5 Min	1	0 - 5 Min
5 - 15 Min	2	5 - 15 Min
15 - 30 Min	3	15 - 30 Min
30 - 60 Min	4	30 - 60 Min
More than 60 Min	5	More than 60 Min

(5) COMPLEXITY	RATING	REPEATABILITY (6)
Very simple-single piece	1	Unlimited
Simple - one moving part	2	10 - 20 operations
Simple - more than one moving part	3	5 - 10 operations
Complex - some moving parts plus power	4	2 - 5 operations
Complex - many moving parts plus power	5	Limited to one operation

TABLE IV-3 (CONTD)

RATING SCALE FOR MISSION SUITABILITY MEASURANDS

MISSION SUITABILITY MEASURAND

RATING

(7) STATE OF DEVELOPMENT		POWER (8)
On shelf	1	No power required
Needs minor modification	2	Requires less than 10 w
Needs major modification	3	10 - 50 w
Only partially developed	4	50 - 100 w
Idea only -- needs development	5	More than 100 w

(9) WEIGHT		VOLUME (10)
Less than 1 lb	1	Less than 5 $in.^3$
1 - 2 lb	2	5 - 25 $in.^3$
2 - 4 lb	3	25 - 100 $in.^3$
4 - 8 lb	4	100 - 200 $in.^3$
More than 8 lb	5	More than 200 $in.^3$

(11) OPTIMUM TYPE SAMPLE ACQUISITION	
Undisturbed samples	1
Representative samples	5
Non-representative samples	10

TABLE IV-4

OBJECTIVE RATING CHART OF SAMPLING INSTRUMENTATION

TECHNIQUE	TOOL	RELIABILITY	HAZARDS	SETUP TIME	OPERATING TIME f(MATERIAL)	COMPLEXITY	REPEATABILITY	STATE OF DEVELOPMENT	POWER	WEIGHT	VOLUME	TYPE SAMPLE	TOTAL GRADE	RATING PREFERENCE
Hammering	Geologist's Pick	1	3	1	1	1	1	1	1	2	2	1	15	1
Sawing	Carbide Tip Hand Saw	1	2	1	2	1	3	2	1	1	2	1	17	3
Cutting	Bowie Type Knife	1	2	1	2	1	2	2	1	1	2	1	16	2
Scooping	Sample Scoop	1	1	1	1	1	1	2	1	1	3	5	18	4
Grasping & Holding	Planchet Forceps	2	1	1	1	2	2	2	1	1	1	5	19	5
Boring	Powered Rotary Tool	3	2	2	3	5	3	4	5	5	5	1	38	8
Hammering Boring Sawing	Powered Impact Tool	3	4	2	2	5	2	4	5	5	5	1	38	8
Magnetic Attraction	Alnico Magnet	1	1	1	1	1	1	1	1	1	1	5	15	1
Passive	Erosion Sampler	2	1	1	4	2	5	5	1	2	4	5	32	7
Passive	Adsorbers	2	1	1	5	2	5	3	1	2	2	5	29	6

- Sawing and cutting are indicated as items 3 and 2, respectively on the rating chart. These two items are recommended for incorporation into a single tool similar to a fish knife. The serrated edges of the knife would consist of sharpened tungsten carbide tips.

- The two powered tools are components of a flexible tool discussed in a later section. Because the impact tool is more versatile and of more value as a separate component than the rotary, this impact tool should have a higher rating.

- While the erosion sampler and adsorber do not truly satisfy sampling needs of the various study groups, they have been included because sampling is inherent in their passive operation. Their objective rating preference is higher than that of the power tools but the immediate need for them and their contribution is far less. Therefore, this type instrumentation was rated lowest of all sampling tools.

b. Preference Rating, Weight and Volume of Sampling Equipment

Table IV-5 shows the revised preference rating of sampling tools plus their accessories, usage, weight, and volume. Their total estimated weight and volume is 40 lb and 600 in.^{3} exclusive of packaging. If 25 per cent additional weight and 100 per cent additional volume is assigned for packaging, the total weight and volume would be 50 lb and 1200 in.^{3} They would fit in a package measuring approximately 16 x 10 x 8 in.

Carrying this amount of sampling equipment on the early missions may hot be feasible. Order of preference indicates that the simplest tools can be packaged to provide all essential sampling techniques. For example, if constraints for sampling tools are 5 lb and 100 in.^{3} for the first mission, the first 4 items would fit these constraints and still provide capabilities for pounding, breaking, cutting, sawing, scooping, scraping, grasping, and holding.

c. Recommendations and Modifications for Simple Tools

1) Hammer, Saw-knife, Sample Scoop, and Chisel

Combining the hammer, saw-knife, sample scoop, and chisel into one unit would save weight and volume. The incorporation of flexibility

TABLE IV - 5

EARLY MISSION PREFERENCE RATING OF LUNAR SAMPLING TOOLS

SAMPLER	ACCESSORIES	TECHNIQUE & USAGE	WEIGHT lb	VOLUME in^3	ORDER OF PREF.	
Geologist's Hammer	Shielding Magnet	Pounding & Breaking - Hardrock Surface Samples Sample Differentiation	H=1.5 S=0.5 M=0.2	20 12 0.5	1	
Modified Fish Knife		Cutting & Sawing - Consolidated Surface Samples	1.0	12	2	
Sample Scoop		Scooping & Scraping - Unconsolidated Surface Samples	0.5	24	3	
Planchet Forceps		Grasping & Holding - Loose Surface Samples Meteoroids, Paleontological, Biological	0.4	2.5	4	
Impact Rotary-Impact Power Tool	Power Pack Electric Motor Auger Core Bit Hammer Chisel Saw Anchor Bolts Clay Digger Adaptor	Pounding, Breaking & Sawing Surface Sampling Subsurface Sampling Making Hole Anchoring & Entrenchment Ground-Instrument Coupling	27	362 Est.	5	Flexible Tool
Rotary Power Tool	Auger Core Bit Modified Hole Saw	Boring Surface Samples Subsurface Samples Making Hole	6	95 Est.	6	
Erosion Sampler		Near Surface Particle Entrapment	1.0	36	7	
Adsorbers		Heavy-Inert Gases	2.0	36	8	

Figure IV-1. Active Mode -- Hammer, Chisel and Shielding

into the design of simple tools may not be feasible since the tendency to cold weld in space may be very strong (Forsyth, 1962; Maguire, 1963).

Use of the chisel and hammer with mesh shielding as a guard for flying chips is shown in Figure IV-1.

2) Planchet Forceps

The only modification anticipated for the forceps is the use of non-metallic claws or metallic claws with a plastic coating to prevent metal-to-sample contact.

3) Erosion Sampler

The erosion sampler is intended as a tool to measure and trap any particles which may be in motion near the lunar surface. This passive device will yield a particle count vs time as well as a representative sample of any type of material in motion. A possible approach to the design of this type sampler is shown in Figure IV-2a.

The instrument consists of a small folding unit of two collecting pans and two drumhead baffles. The first pan and baffle collects particles from the surface to 6 in. and the second combination from 6 to 12 in. elevation. The baffle serves two purposes; to deflect slow-moving particles into the pan and to collect within the drumhead the fast-moving particles that penetrate the outer skin. More complex units of this type would also measure velocity and angle of impact.

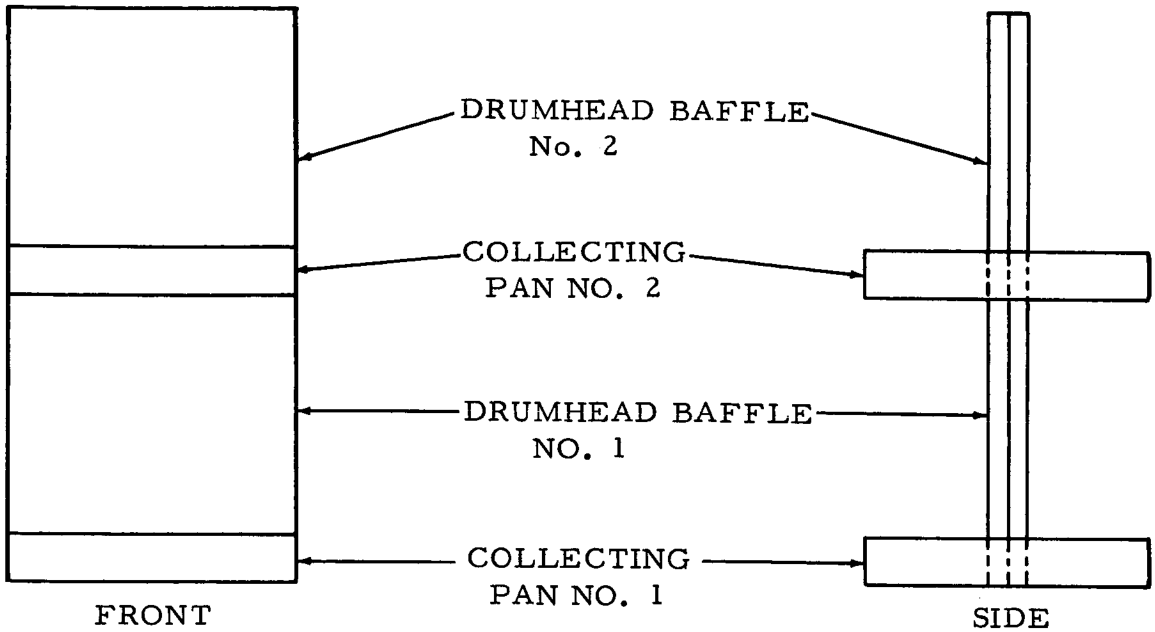
4) Adsorbers

The adsorbers are intended as a means of gas sampling of a possible lunar atmosphere. Two units are necessary to make valid tests of this type. These units would consist of 3 or 4 compartmented adsorbing agents such as activated charcoal, titanium sponge or activated alumina (Figure IV-2b). They should be packaged and sealed under controlled conditions on earth so that no difference in content can be detected. The two units would then be carried to a suitable spot on the lunar surface and one of the units activated by exposure. After some time, the exposed unit would be re-sealed and returned with the control unit to earth where accurate quantitative comparisons could be made.

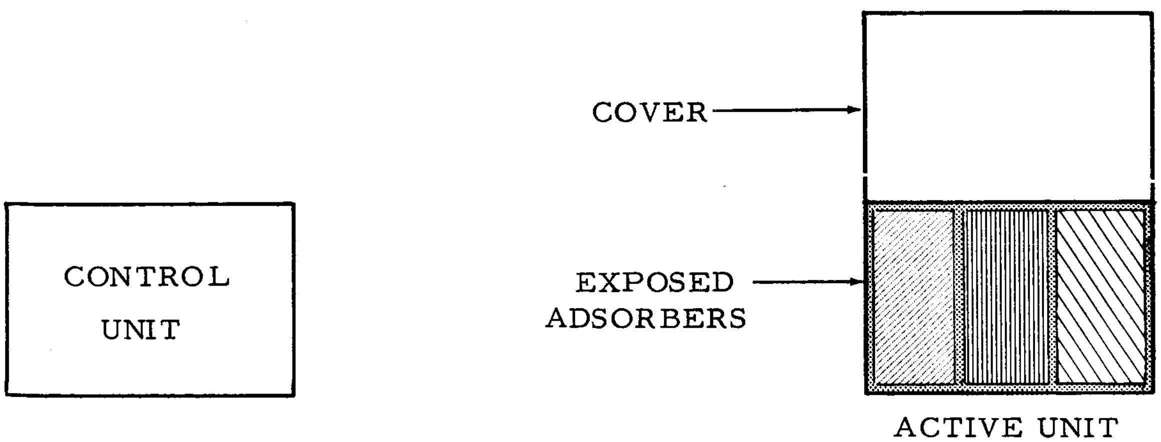
d. Recommendations and Modifications for Complex (Powered) Tools

A definite need exists for a powered tool capable of extracting surface and subsurface samples to extend the sampling range of simpler tools. This instrument should be capable of obtaining undisturbed samples and yet be designed to extract any sample type regardless of the nature of the lunar surface. Any design of a flexible tool should have as its primary-use factor the collection of surface samples since surface measurements must precede subsurface sampling. Subsurface sampling and hole making should be considered as desirable but secondary products of extending the use of the original tool (Figure IV-3).

The flexible tool should consist of a separate rechargeable power pack and two components incorporating rotary, percussive and rotary-percussive action (Figure IV-4). The 3-way action can be incorporated into a



(a) Particle Movement Sampler



(b) Adsorbers -- Control and Active Units

Figure IV - 2. Erosion Sampler and Adsorbers

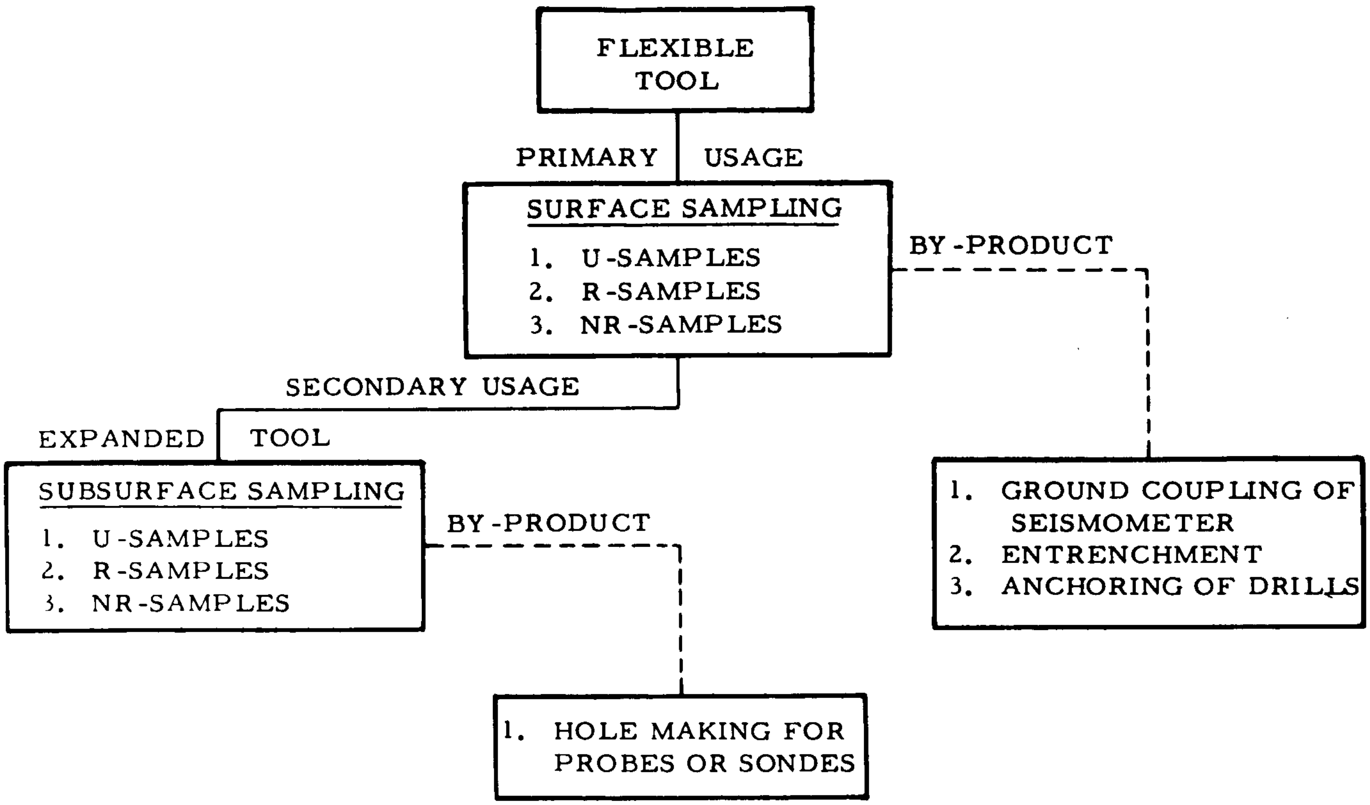


Figure IV-3. Flexible Tool Usage for Design Considerations

single component, however, this type unit may be unduly complex and more readily subject to breakdown in the lunar environment.

The 3-way action of the two components would be utilized in sampling and making hole as follows:

Action	Drilling Medium	Usage
Rotary	Soft-medium rock	Surface and subsurface sampling -- small cores (1 in.). Depth to 5 ft. Large surface cores to 4 in. diam. Holes for probes.

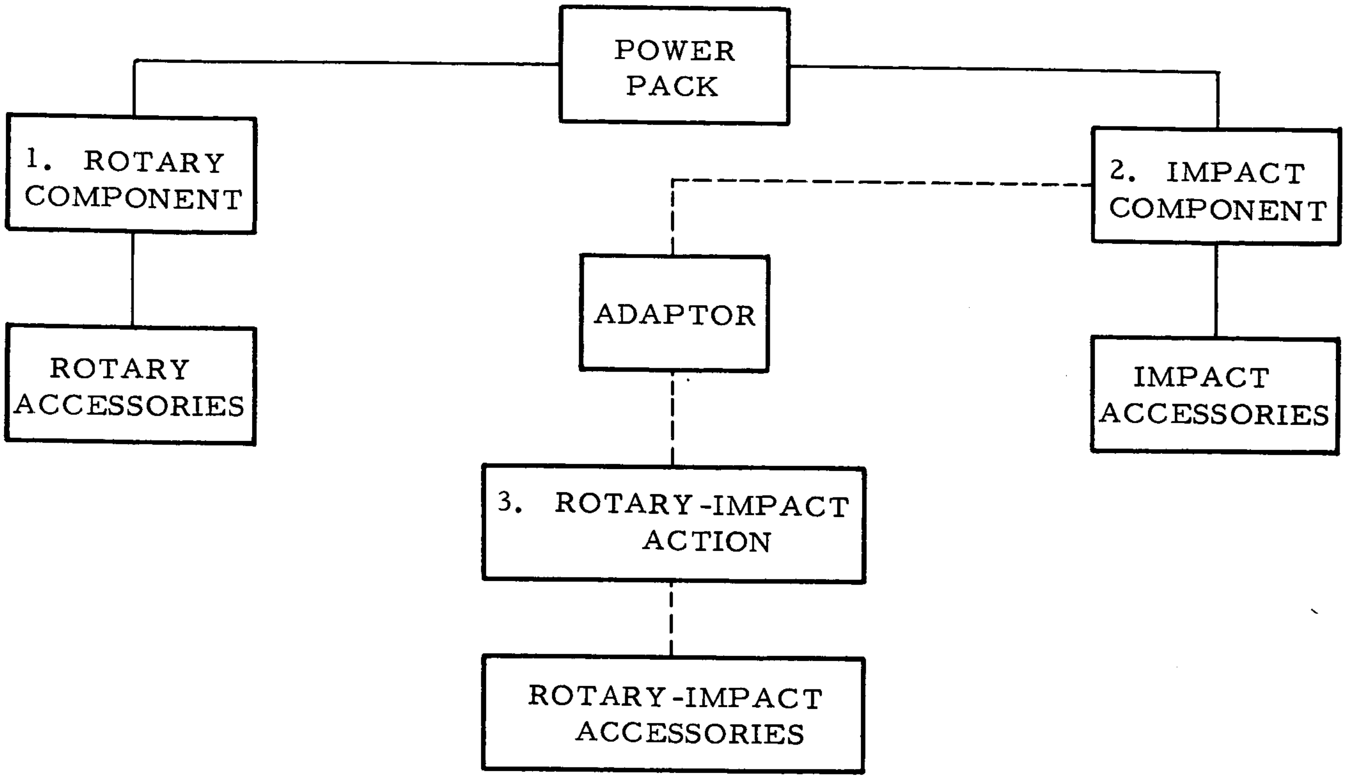


Figure IV-4. Flexible Tool and Sampler Scheme

Action	Drilling Medium	Usage
Impact	Hardrock	Surface sampling. Removal of "in place" rock by hammering, chiseling and sawing.
Rotary-Impact	Hardrock	Surface and subsurface sampling -- small broken core samples (3/4 in.). Depth to 5 ft. Holes for probes.

Use of a tool capable of generating this 3-way action should be to insure the acquisition of lunar samples regardless of the nature of the lunar surface and prove of value in other aspects of the APOLLO program. Other possible uses of this type tool are listed below:

- Provide means for coupling and emplacement of seismometers
- Anchoring and entrenchment of drilling devices and telemetry antennae
- Making hole
- Breaking and cutting blocks of pumice-like or frothy material for shielding or base construction

Prime considerations in the development of a tool of this type are:

- Capability of acquiring all types of samples from undisturbed to non-representative
- Weight
- Power requirements
- Volume
- Mechanical removal of cuttings
- Capability of expansion
- Environmental-engineering problems (dissipation of heat, lubrication, etc.)

Based on these considerations, the following principles should be considered in the tool's development:

- 3-way mechanical action to insure acquisition of a sample by coring, hammering, chiseling, or sawing
- Bottom-hole drilling, rotary and rotary-impact. Suitable adapters to be provided for downhole or uphole use of the electric motor
- Use of a modified double-tube auger bit for simultaneous acquisition of a core sample and downhole retention of drill cuttings
- A modified bonnet and spring arrangement (Armour Research, 1961) to apply pressure on the bit from an anchored frame on the surface

- Extension rod or drill stem to act as the power transmission line without the use of cabling

- Adapters for converting rotary or impact motion to rotary-impact motion

- Modified accessories for sampling entrenchment and anchoring of other instruments

Some advantages of this type of tool are:

- Extreme flexibility -- On early missions it may be desirable to take only portions of the tool for rapid surface sampling; accessories and drill stem can be added on later missions as they appear to be needed.

- Sample acquisition dependability -- Incorporation of 3-way action should insure the acquisition of a sample regardless of the nature of the lunar surface.

- Low weight, power and volume for extension of the tool to a shallow hole drill. Design of bit eliminates need for double-tube auger stem from bottom hole to surface.

- Would not require use of fluids or gases for removal of drill cuttings.

- Can be used as a surface or subsurface sampler and to make hole for the insertion of measuring sondes.

- Easily expanded by increasing power and modifying bit and stem.

- Fulfills other needed requirements of early APOLLO missions such as entrenchment and anchoring of drill frames and antennae.

A disadvantage of this type bottom-hole drill is the numerous round trips required to remove core samples and cuttings. Since continuous sampling is desirable, this may not be a disadvantage in the early missions. Round trips, in shallow holes, will be simple and rapid since the total expected moon weight will not exceed 4 or 5 lb. Lengthening of the bit will decrease the number of round trips but will also increase the amount of power needed for operation.

e. Recommendations for Sample Containers

No suitable on-shelf containers are available for storage and transfer of lunar samples. The major constraints imposed on the selection of containers are weight and volume, which will necessarily restrict the use of solid inflexible vessels. Studies should be directed toward developing the following types:

- Small reinforced metal containers fitted with ultravacuum tight covers for returning undisturbed and biological samples in an uncontaminated state (size -- 1.5 x 6 in. cylinders)

- Square or ellipsoidal containers, with full covers and valve fittings, for the preservation of samples showing unusual mechanical structure. The valve serves two purposes: 1) for the injection of a quick hardening liquid plastic and 2) as a safety pop-off valve (size -- 3 x 3 x 3 in.)

- Sampling bags, with flap seals, formed of a pliable material capable of withstanding the lunar environment and which can be molded to the shape of the sample (envelopes -- 5 x 7 in.)

- Open end container for acquisition of known volume of unconsolidated material for bulk density measurements

Consideration should be given to storage of the total volume of samples in one container with an ultravacuum-tight seal in order to:

- Insure against contamination of the samples by the earth's atmosphere

- To avoid possible bacterial contamination of the earth's atmosphere or surface by lunar samples

The most simple and direct approach toward accomplishment of this task would be to construct the LEM sample bin with a snugly fitting inner liner that can be sealed or to construct it as a sealable, removable unit.

TABLE IV-6

EXAMPLE OF A SAMPLE CONTAINER PACKAGE

TYPE CONTAINER	NO.	SIZE (in.)	WEIGHT (lb)	VOLUME (in.^{3})
Ultravacuum-tight containers	4	1.5 x 6 cylinders	2.0	54
Mechanical structure container	1	3 x 3 x 3 square	0.4	27
Plus preservative		1 x 6	1.0	6
Sampling bags	15	5 x 7 x 0.06	1.5	33
Total	20		4.9	120

The total volume (see Table IV-6) is less than 400 in.^{3} when each sample bag is filled with approximately 20 in.^{3} of sample. This volume of samples can be stored easily and sealed in the LEM bin for return to earth.

A combination of vessels of the above general description should satisfy weight and volume requirements and still provide adequate protection for sample return.

f. Recommended Instrument Packages

Three sampling tool packages are listed in Table IV-7. The recommended sampling tools and containers are intended to fulfill the excursion time requirements for 2, 4.5 and 9.5 hr missions.

The weight and volume estimates are based on anticipated modifications for the simple tools and on future developmental needs for the complex tools and sample containers. The time estimates for extracting samples are more truly time allotments for different techniques. For example, if one technique is not applicable, the time should be allotted to those techniques that do apply to the extraction of a sample. The total time allotted is based on the assumption that a heterogeneous surface exists which requires the use of all the listed sampling techniques and very careful packaging of samples in individual containers. If a homogeneous surface exists which requires the use of only two or three sampling techniques and two or three large sample containers, the required time can be greatly reduced (15-20 min), figures which are compatible with the sampling times shown in the Flight Plans, Part I, Chapter II.

Sample instrumentation packages have been designed to cover a wide variety of sampling techniques to insure maximum data return.

TABLE IV-7

RECOMMENDED INSTRUMENTATION PACKAGES

Sampling Tool Package No. 1 — Total Excursion Time 2 hr

Sampler	Weight (lb)	Volume (in.^{3})	Power (w/hr)	Allotted Time
Geologist's hammer and chisel	1.5	20.0	--	3 samples -- 15 Min
Shielding	0.5	12.0	--	
Magnet	0.2	0.5	--	
Sample scoop	0.5	24.0	--	3 samples -- 3 Min
Planchet forceps	0.4	2.5	--	3 samples -- 3 Min
Saw-knife	1.0	12.0	--	1 sample -- 5 Min
Ultravacuum tight containers (6)	3.0	90.0	--	18 Min
Sample bags (26)	2.6	39.0	--	26 Min
Subtotal	9.7	200		70 Min
Packaging requirements	1.0	50		
Total requirements	10.7	250		70 Min

RETURN PACKAGE

Containers	Est. Weight* (lb)	Est. Volume (in.^{3})	Est. Package Size (in.)
Ultravacuum tight containers (6)	11.1	90.0	
Sample bags (1 = 20 in.^{3}) (26)	57.2	520.0	
Subtotal	68.3	610.0	
Packaging requirements	1.0	140.0	
Total return-Wt., Vol., Size	69.3	750.0	10 x 10 x 8

*Avg. Density = 0.11 lb/in.^{3}

TABLE IV-7 (CONTD)

RECOMMENDED INSTRUMENTATION PACKAGES

Sampling Tool Package No. 2 Total Excursion Time 4.5 hr

Sampler	Weight (lb)	Volume (in. ^{3})	Power (w/hr)	Allotted Time
Geologist's hammer and chisel	1.5	20.0	--	4 samples -- 20 Min
Shielding	0.5	12.0	--	
Magnet	0.2	0.5	--	
Sample scoop	0.5	24.0	--	3 samples -- 3 Min
Planchet forceps	0.4	2.5	--	5 samples -- 5 Min
Saw-knife	1.0	12.0	--	1 sample -- 5 Min
Ultravacuum-tight containers (5)	2.5	75.0	--	15 Min
Mechanical structure container and preserver (2)	2.8	66.0	--	10 Min
Sample bags (24)	2.4	36.0	--	24 Min
Subtotal	11.8	248.0		82 Min
Packaging requirements	1.0	75.0		
Total requirements	12.8	323.0		82 Min

RETURN PACKAGE

Containers	Est. Weight* (lb)	Est. Volume (in. ^{3})	Est. Package Size (in.)
Ultravacuum-tight containers (5)	9.3	75.0	
Mechanical structure container (2)	6.8	64.0	
Sample bags (1 = 20 in. ^{3}) (24)	52.8	480.0	
Subtotal	68.9	619.0	
Packaging requirements	1.0	150.0	
Total return-Wt., Vol., Size	69.9	769.0	10 x 10 x 8

*Avg. Density = 0.11 lb/in. ^{3}

TABLE IV-7 (CONTD)

RECOMMENDED INSTRUMENTATION PACKAGES

Sampling Tool Package No. 3 Total Excursion Time 9.5 hr

Sampler	Weight (lb)	Volume (in.^{3})	Power (w/hr)	Allotted Time
Geologist's hammer and chisel	1.5	20.0	--	5 samples--25 Min
Shielding	0.5	12.0	--	
Magnet	0.2	0.5	--	
Sample scoop	0.5	24.0	--	3 samples--3 Min
Planchet forceps	0.4	2.5	--	4 samples--4 Min
Saw-knife	1.0	12.0	--	2 samples--10 Min
Flexible tool-all components	33.0	457.0	400	6 subsurf. samples 2 holes--120 Min
Erosion sampler (1)	1.0	36.0	--	Setup--pickup-- 6 Min
Adsorber units (2)	2.0	36.0	--	Setup--pickup-- 3 Min
Ultravacuum-tight containers (8)	4.0	120.0	--	24 Min
Mechanical structure container and preserver (2)	2.8	66.0	--	10 Min
Sampling bags (22)	2.2	33.0	--	22 Min
Subtotal	49.1	819.0	400	227 Min
Packaging requirements	2.0	200.0		
Total requirements	51.1	1019.0	400	227 Min

RETURN PACKAGE

Containers	Est. Weight* (lb)	Est. Volume (in.^{3})	Est. Package Size (in.)
Ultravacuum-tight containers (8)	14.8	120.0	
Mechanical structure container (2)	6.8	66.0	
Sample bags (1 = 20 in.^{3}) (22)	48.4	440.0	
Subtotal	70.0	626.0	
Packaging requirements	1.0	150.0	
Total return-Wt., Vol., Size	71.0	776.0	10 x 10 x 8

*Avg. Density = 0.11 lb/in.^{3}

5. Conclusions

Present knowledge of the lunar surface is essentially conjectural and will remain so until on-site studies are made. The success of later missions will be dependent on these initial on-site studies and on analyses of lunar samples returned to earth. The importance of obtaining any sample is recognized, and maximum effort should be expended to get a sample or samples regardless of the nature of the lunar surface.

The basic sampling problem is to acquire samples yielding the maximum scientific and technologic data. Non-representative samples would contribute a great deal to knowledge of the lunar surface, but this type of sample is relatively unsuitable when compared to the amount of data that could be obtained from representative and undisturbed samples.

Any "in place" piece of material that is extracted can be considered an undisturbed sample whether obtained by coring, impact drilling, sawing, or cutting. Small cores of known size would simplify the design of ultravacuum-tight vessels. Use of such vessels should pose no great problem for containment of small odd shapes except for loss or waste of assigned volume. Large undisturbed samples will be advantageous if the material sampled contains large vesicles. Since hammering and sawing may present some hazards, the astronaut must elect the method most suitable to the conditions.

The present study has related a "type" sample to the tests for which it is required. This has resulted in a gross evaluation of the scientific and technologic data obtainable from each specific "type" sample. Instrumentation and techniques were then related to these specific types of samples on the basis of their sampling capabilities (see Figure IV-5).

Results of the sampling survey shows the need for packaging sampling equipment of minimum weight and volume to cover a wide variety of sampling techniques. The more simple tools will naturally take precedence over any powered tools for initial phases of lunar sampling because of their postulated reliability, low weight and volume. The need exists, however, for design and development of a flexible tool to extend the range of surface sampling and also to obtain subsurface samples. Important by-products of a powered sampling tool would be shallow holes for measuring sondes, anchoring and entrenchment.

The art of sampling includes a vast array of principles and instrumentation. This study has related specific types of samples to sampling techniques and instrumentation to increase the probability of acquiring suitable samples regardless of surface conditions.

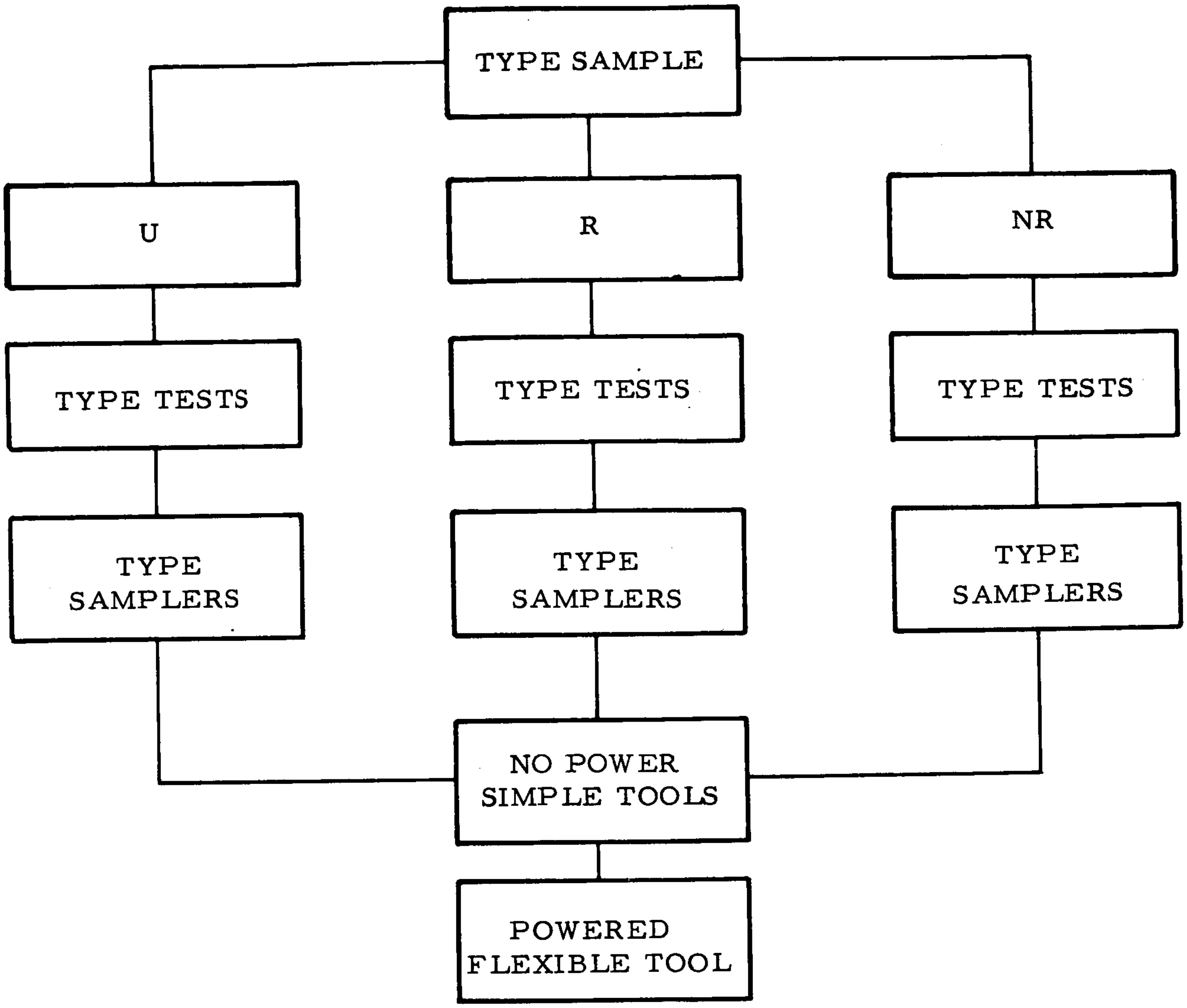


Figure IV-5. Sample-Instrumentation Relationship

C. SURVEYING, MAPPING AND PHOTOGRAPHY

1. Review of Lunar Requirements

a. Summary

Reasons for engaging in these activities on the moon are to:

- Provide the necessary survey ties to remote sensor and other data for extrapolation of APOLLO observations over wider areas
- Measure and map surface characteristics pertinent to hazards, basing, trafficability, and scientific studies. These data must be recorded rapidly and accurately in great detail.
- Survey elevation and position differences with sufficient accuracy to make necessary geophysical corrections and computations
- Obtain data on the shape of the moon

b. Extrapolation of Point Data

1) Lunar Area Investigated by Early Missions

The percentage of the moon's visible surface that can be investigated on the first two APOLLO landings is very small. Assuming the moon is a sphere with a radius of 1080 mi, the half facing the earth has an area of 7,329,000 sq mi. During two missions, the astronaut may spend about 14 hr investigating the lunar surface. If he can geologically scan at the rate of 500 ft/hr, make intelligent observations and select key samples over a distance of 50 ft on each side of his traverse, he would investigate 50,000 sq ft/hr. This would be 700,000 sq ft in 14 hr, or 0.025 sq mi.

A less conservative estimate would be to assume that all anomalous features within the astronaut's operating radius would be investigated. If the astronaut can investigate selected areas within 1000 ft of the LEM, the total area "investigated" would be 3.14×10^6 sq ft or 0.11 sq mi per mission.

2) Requirements for Extrapolation

The first requirement is orbital photography with resolution as good as power, weight and volume constraints will permit. Lunar Orbiter photography available for the APOLLO mission will have a ground resolution of about 9 ft per optical line pair in the high resolution mode (Kolcum, 1963).

The next requirement is to locate the observation and sample sites relative to the photographic properties of the sample area. These properties are tone, color, texture, pattern, shape, and size (see Chapter I, Section D).

Gradational relationships defined by changes in tone, color and texture that may be clearly shown on the photographs could be difficult for the astronaut to decipher on the lunar surface because of the lunar photometric function. The brightness of the illuminated areas will vary with the sun-surface-eye angle, and the shaded areas will be black. Brightness would therefore vary with slope, direction and distance of the surface from the astronaut.

For these reasons, the observations must be tied to lunar structures having sharply defined edges recognizable as having definite pattern, shape or size on the orbital photographs. These structures may be intersections of cracks, joints, faults, or small rilles, and volcanic, impact or splash craters.

3) Location of Sample and Observation Sites

Many features will be too small to be recognizable as discrete objects on the orbital photography but may contribute to photographic tone, color and texture. Since other features with gradational tonal boundaries may not be mappable on the surface, it will be helpful to locate the sample and observation sites in two steps.

Step 1 will be to tie the LEM precisely to surface features, such as craters, that can be recognized on the Orbiter photography and easily identified on the ground.

Step 2 will be to tie the sample sites to the LEM by using it as a fixed stadia reference point.

c. Requirements for Measuring and Recording Surface Characteristics

1) Hazards

Hazards, observations and measurements would involve photography of surface debris, slopes and dust thickness. Sharp-edged debris could cut the space suit. Rough, very steep slopes and slopes showing signs of sliding would be dangerous to climb.

2) Trafficability

Trafficability studies will require a detailed map of the area to provide data for vehicle design. Relief, strikes, slopes, and spatial relationships of topography down to a relief of a few inches are important.

Also important is a means to record particle sizes of surface dust, debris and breccia, and the depth of penetration of the astronaut's footprints. The simplest way to record details would be to use descent and hand camera stereo photography.

3) Basing

Basing requirements include the hazards and trafficability measurements and the dimensions of any lunar feature, such as a rille or lava cave, that would partially fulfill shelter needs.

4) Scientific

These measurements are primarily concerned with the survey, mapping and photographic needs of the geologist and geophysicist. The geologist will require bearings accurate to about 1/2°, distance differences to about 1 ft in 500 ft, dips accurate to 1° or 2°, orientation of some drill cores to lunar north, photography to record the geologic background at sample sites, and the measurements listed under the previous headings.

d. Corrections for Geophysical Measurements

1) Gravity

Gravity measurements must be corrected for changes in elevation relative to some arbitrary datum. The combined free air and Bouguer correction on the moon (see Chapter II, Section B, Gravity) is about 0.10 mgal per meter. If the gravimeter has a working accuracy of 0.03-0.05 mgal, the survey must be accurate to about 1/3 to 1/2 meters.

Terrestrial surveys are corrected for changes in latitude because of polar flattening. A lunar bulge towards the earth would cause a similar effect, but it may be too small to be detected over the limited distance traversed by the astronaut. The gravity effect for a bulge of 1 kilometer, for example, may be no more than 190 mgal. If this effect is distributed over the 1080-mi-distance from the center of the moon to one edge as seen from earth, the gradient per mi would be about 0.18 mgal. The observed effect would be on the order of 0.03 mgal per 1000 ft in a direction towards the center of the bulge.

Gravity stations should be located relative to the LEM to an accuracy of 1 part in 500 so that the Bouguer gravity values can be accurately contoured.

2) Magnetics

There need be no corrections for magnetic station elevations, but the observation points should be located to about 1 part in 500 to insure accurate contouring of the data.

3) Seismic

Seismic measurements must be corrected for the distance and elevation difference between energy input (shotpoint) and energy reception (geophones). Elevation differences should be measured to a precision of 2 or 3 ft, and the distance measured to an accuracy of about 1 part in 500. Profile bearings should be determined to an accuracy of about $1/4°$ to $1/2°$.

4) Electrical

Elevation differences normally are not required for electrical measurements, but the distance between energy input and energy reception should be measured to plot curves for interpretation purposes with an accuracy of 2 or 3 ft per 500 ft.

e. Determination of the Shape of the Moon

Ultimately the precise shape of the moon must be determined as a fundamental requirement for the preparation of more accurate maps, to provide the parameters needed for precise guidance of later space probes and for certain geophysical measurements.

Conventional geodetic surveys employ triangulation schemes to establish known positions and azimuths at various points of the earth's surface. Positions accurate to a few inches relative to one another are established by measuring angles of spherical triangles precisely and carrying computed azimuths and distances through the networks from baselines of known length. Distances can be taped or measured electronically to about 1:300,000. Angle and azimuth measurements in geodetic work involve multiple sets of pointings which are read direct to 0.1 sec of arc. A new geodetic technique involves electronic tracking of satellites whose orbits have been determined precisely.

In all cases the equipment involved is heavy, bulky, time consuming to operate, sensitive to rough handling, and usually requires delicate and tedious adjustments. A theodolite, tripod and timing equipment for an astronomic determination would weigh approximately 100 lb and an electronic distance measuring set about 98 lb. Ground equipment for a geodetic SECOR station (Van Atta, 1964) weighs several thousand pounds, and also requires an orbiting satellite carrying a transponder and a few pounds of electronic equipment.

Because of the APOLLO constraints on weight, power, volume, manpower, and mobility, precise geodetic measurements useful for determining the shape of the moon do not seem possible. Navigational equipment on the orbiting module will provide useful distance and position data but not to normal geodetic accuracy.

Lunar geodetic measurements may eventually be made with navigational satellites designed for lunar use. Heavy electronic packages will probably be orbited, and the light weight transponders dropped on the surface. (This is the reverse of terrestrial practice.)

2. Locating LEM on Moon

a. Introduction

Location of the LEM on lunar surface photographic maps is a prerequisite for the extrapolation of the APOLLO point data over larger areas. Location accuracy for this purpose is a function of the Orbiter photographic resolution. In the high resolution mode its surface resolving power will be about 9 ft per optical line pair (Kolcum, 1963). This should be sufficient to detect long, linear patterns 4-1/2 to 9 ft wide, and to identify and measure the shapes and sizes of structures (such as craters) approximately 23 ft in diameter where sufficient contrast is present(see Chapter I, Section D).

Many location techniques cannot meet these standards. Until a precise shape is determined for the moon and deflections of the local vertical are determined, positions obtained by astronomic observations or by electronic mapping with orbiting navigational aids may not correlate with those obtained by orbital photography by several hundred to perhaps 1000 or 2000 meters.

Locations by resections to distant landmarks will be in error by the amount of scale distortion in the orbital photographic maps. From the Command Service Module at an altitude of 80 mi these distortions can be checked by means of a sextant, a scanning telescope, an inertial measuring unit, a guidance computer, coupling-decoupling units, and associated electronic packages. According to NASA (1963, Study of Selenodetic Experiments) the accuracy of the sextant is about 10 sec. If all other errors in timing and pointing could be eliminated, at an altitude of 80 mi, astronomic positions could be positionally misplaced by 300 ft from instrument error alone.

The accuracy of the tracking telescope is about 1 min. Errors from this source would be 120 ft directly below the CSM and would be greater proportionately at longer distances.

If a light could be created that would be intense enough to be seen by terrestrial telescopes, the LEM could be located relative to features on lunar photographs taken from earth. These would not be sufficiently accurate for locating the LEM on the best Orbiter photographs because the theoretical limit of a 300-ft focal length telescope with a 60-in. aperture is about 0.077 sec (Martz, 1963). This is equivalent to 500 ft on the lunar surface, and it seems doubtful that sufficient power could be made available for such an experiment even if it were desirable.

The use of angle encoders to measure bearings from earth to transponders on the LEM would be less accurate than the observatory telescopes. The Microgon encoder (Colorado Research Co.) measures angles to 0.618 sec which would be equivalent to about 3/4 mi on the moon.

The above arguments suggest that astronomic positions, bearings on distant landmarks, light flashes, or electronic signals to earth would not be sufficiently accurate to fully utilize the Orbiter photography for extrapolation of data. The ideal system would be to use this photography directly for locating the LEM in some way. Four methods by which this might be accomplished are:

- Photographs of LEM from Command Service Module
- Pilotage and dead reckoning on Orbiter photographs during LEM descent
- Nested photography during descent
- Bearing and distances to near landmarks

b. Photographs of LEM from Command Service Module

Trying to locate the LEM on the lunar surface using orbital photography may be as difficult and uncertain as locating a life raft at sea. The LEM is 16 ft in height and with the sun 30° above the horizon, it will cast a shadow approximately 28 ft in length.

At first glance it would seem possible to use the Orbiter camera in the Command Service Module (CSM) for this purpose because its ground resolution is about 9 ft per optical line pair. The Lunar Orbiter Camera will be used to take photographs at altitudes of 22-29 mi, but the CSM will orbit at 80 to 100 mi. As a consequence the same camera's ground resolution would be only about 1/3 to 1/4 the resolution of the Orbiter photographic mission, so its resolving power would decrease to 27 - 36 ft per optical line pair.

Another problem is that the LEM will move out of the CSM orbit plane at the rate of 1.07° or 108,000 ft on the equator for each 2-hr orbit. If the orbit plane is inclined 40° to the equator, the closest approach, X, will be:

$$X = 108,000 \times \text{Sin } 40° = 69,400 \text{ ft}$$

For a vertically oriented camera to see the LEM 69,400 ft to one side of the ground track after the first orbit, the ground coverage must be 138,000 ft. If an altitude of 80 naut mi is used for the CSM (Sears, 1964), the view angle of the camera can be estimated as shown in Figure IV-6.

The ground coverage per line, G_{cl}, with this view angle can be computed with the following (see Chapter I, Section D-8) expression:

$$G_{cl} = \frac{2A \text{ Tan } (\theta/2)}{F\ S} \qquad (1)$$

Where:

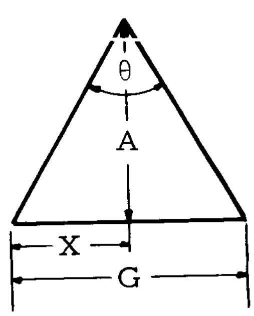
A = 486,400 ft

F = Film format, about 60 mm for 70 mm film, for compact aerial camera

S = Film-camera resolution assumed to be about 30 lines/mm

θ = Camera view angle

$$G_{cl} = \frac{2 \times 486,400' \times 0.143}{60 \times 30} = 77 \text{ ft per film-camera resolution line.}$$



A = Altitude 486,400 ft

X = Closest approach = 69,400 ft

G = Ground coverage = 138,800 ft

θ = Camera view angle in degrees

Then: $\text{Tan } (\theta/2) = X/A = 69,400/486,400 = 0.143$

Figure IV-6. Camera View Angle at 80 Nautical Mile Altitude

This would not be sufficient to detect a 28-ft shadow. If a larger camera is used, the weight would be excessive and the improved resolution would not be enough to assure detection. If a 9-in format camera is used, such as the 135-lb Hycon HR-320, the G_{cl} would be:

$$G_{cl} = \frac{2 \times 486{,}400' \times 0.143}{(9 \times 25.4 \text{ mm}) \times 30} = \text{21 ft per film-camera resolution line.}$$

A ground resolution of 21 ft could be sufficient to detect the LEM but may not be sufficient to identify it. In any event the CSM would not be able to carry a camera as heavy and as bulky as the HR-320.

A light weight, 70 mm, vertically oriented camera could not detect the LEM from the CSM 80-mi orbit altitude with the sun 30° above the horizon. Detection may be possible with a very low sun, with a string of lights at night, by pointing the camera offtrack slightly and using a longer focal length lens, or if the LEM moved out of the CSM orbit plane the proper amount during descent. These are special situations, therefore alternate techniques should be considered.

c. Pilotage and Dead-Reckoning During Descent

Pilotage and dead-reckoning would have the advantage of using equipment currently assigned to the LEM including landing radar, guidance computer, alignment optical telescope, inertial measurement unit, window reticles, and map display units. By using this equipment, the pilot should be able to land and locate himself in the area covered by 1:20,000 or 1:25,000 landing maps prepared from Orbiter photography.

Disadvantages of this technique are that the pilot has very limited visibility for doing accurate pilotage. Also, he will be more concerned with making a safe landing than he will be with precise pinpointing of his position relative to lunar surface features.

After landing, the pilot could find himself in one of the following situations as far as location is concerned:

- Hopefully, he identified a topographic form on the landing chart and was able to land close enough to it to gauge its location by hand-held stereo photography or by surveying measurements. This would fulfill the primary objective of relating the landing site to lunar photographic characteristics.

- The pilot astronaut identified a landmark during landing but came down too far from it to make a survey tie. The features within the roving astronaut's range can not be resolved or identified on the landing site photographs in terms of shape and size but appear as variations in texture. This will not satisfy the primary objective for relating the site to photographic features.

- The pilot astronaut saw several landmarks in the landing area; but in his preoccupation with making a safe landing, he was unable to positively identify any one feature. It may be possible for the roving astronaut to make ties to enough of these features to unambiguously locate the LEM; if not, the LEM location could be in doubt. The latter case could lead to a miscorrelation between surface features and photographic characteristics.

- The landing area is flat and featureless on the Orbiter photographs but contains many small structures far below the orbital camera resolution.

- The pilot did not land in an area mapped by the Orbiter photography.

The last four of the cases will not fulfill the primary objective of locating lunar features on Orbiter photography. Therefore, the data collected by the astronaut could not be put to maximum use. The technique, although helpful, cannot be considered fully reliable, and additional safeguards should be considered.

d. Nested Photography During Descent

1) Introduction

If new pictures could be taken during the descent from orbit, these photographs leading to the actual landing site could be correlated with previous Orbiter photography to locate accurately the landing area on the photograph.

The photographs also would provide additional, high-resolution detail on minor structures below the resolution of the Orbiter photographs and would record any disturbances of surface features by the rocket landing blast. The picture could be used in the event of a landing abort to verify the pilot's judgment and to replan the next mission.

Such a camera would have to be light and compact; it should have automatic film advance, good resolution, image motion compensation, and a large view angle. Quite probably a 70-mm camera with fixed focus lens would be satisfactory.

The amount of film, cycling time to produce the proper overlap, the image compensation, and the required exposures should be computed for each camera and mission considered. Key camera parameters are the view angle, film size, negative format size, and the film used. Mission parameters are altitudes, descent times and ground velocity.

2) Camera and Mission Parameters

If the camera used is similar to the Itek Day/Night Camera and the mission profile follows the data given by Sears (1964), the amount of film, cycling time, image compensation, and exposure level can be estimated. The camera parameters are as follows:

View angle	58.6°
Film size	70 mm
Format	57 mm
Picture overlap	At least 40 per cent
Focal length	52 mm

3) Image Compensation

The image compensation can be computed from the formula presented in the Appendix of U. S. Air Force Manual 95-3 (1961).

$$\text{Vel} = 1.69 \frac{V}{H} F \sin\theta \qquad (2)$$

Where:

Vel = Velocity of film in in. /sec

V = Ground speed in knots

H = Altitude in ft

F = Focal length in in.

Sin θ = Sin of depression angle

Sin 90° = 1

By using the above formula at various points during the descent and estimating the average ground speed, the average image compensation is about 0.247 in./sec. The initial picture at 50,000 ft for instance, the LEM velocity is 5581 ft/sec for a ground speed of approximately 3305 knots (neglecting the moon's rotational velocity of about 9 knots).

$$\text{Vel} = \frac{1.69 \times 3305 \times 2 \times 1}{50{,}000} = 0.225 \text{ in./sec}$$

The image motion will change drastically at low altitudes when the LEM brakes to begin a more vertical descent at about 1000 ft of altitude.

4) Cycle Rate

To obtain a minimum of 40 per cent overlap, photographs would have to be taken at least every 4 to 6 sec. At 50,000 ft the ground coverage would be 56,200 x 56,200 ft. The useful coverage (60 per cent) would be 33,720 ft x 33,720 ft. To travel 33,720 ft to the next frame at 5581 ft per sec would take about 6 sec.

At an interval rate of 4 sec, it would take 112 pictures to cover the 447 sec from 50,000 ft to touchdown. At 70 mm per frame, this would take between 25 and 26 ft of film. This is the present capacity of the Itek Day/Night camera for inflight processing.

The maximum interval rate of the Itek camera is only 3 sec. At 3-sec intervals the overlap would be more than adequate, but it would require 149 frames or 35 ft of film. This is above the 25-ft capacity for inflight processing but within the normal film magazine capacity. For inflight processing the camera should be redesigned to obtain a longer cycle time, or the magazine capacity should be increased.

5) Film and Exposure Levels

The brightness for the lunar surface with the sun about 20° above the horizon would range from about 200 to 570-ft candles for objects in direct sun light, and about 2-ft candles for objects in the shadows.

With Image Motion Compensation (IMC) relatively low-speed films and long exposure times can be tolerated except during the last 1000 ft of descent where blur would be caused more by increasing image size than by lateral image motion.

Multilayer films can be used only if inflight processing is not required. Because of the lunar variations in brightness due to sun-camera angles and slope angles, it may be desirable to use film with a relatively wide exposure latitude such as Kodachrome II (25 ASA) or the Edgerton, Germeshausen, and Grier extended range film. The EG&G has three emulsion layers with ASA (American Standards Association) ranges from 400 to 0.004, and it ordinarily is used with an ASA rating of 40. Exposure for Kodachrome II of about 1/60 sec would be satisfactory except possibly during the last 1000 ft of descent where sharp pictures will be needed to show the area to be sampled by the astronaut.

Normally it will be desirable to employ inflight processing to obtain maps of the work area. In such case a simpler, one-layer film would be used.

A logical candidate for the one-layer film would seem to be the Kodak SO 243 that will be used on the Lunar Orbiter program. It is highly resistant to radiation, its exposure characteristics will be tested under lunar conditions and it is very fine-grained. The main problem is that its ASA rating of 1.6 would be too low for a normal lens at low altitude. Small changes in image motion during descent could also be troublesome if a relatively simple camera is to be used with such a slow film.

According to Taback (1964) the main consideration in choosing the SO 243 film is its resistance to radiation. It can tolerate 200 rads of radiation and still have enough contrast for a reasonably good photograph. Higher speed film would have less resistance; an 80 ASA film could only tolerate about 3 rads.

6) Camera Location

Vertical photographs or oblique photographs at relatively small angles from the vertical would be desirable for most mapping requirements. To simplify camera mounting it would appear desirable to mount the camera on the outside of the LEM and manually control its orientation relative to vertical with a servo motor, or automatically control it with a horizon or some other type sensor. In the event of an abort, however, the film may not be recoverable. and the unfavorable landing condition seen by the astronaut could not be verified on film. Partly for this reason the camera should be mounted inside the LEM; also, inflight-processed film could be used immediately after landing to plan outside traverses, choose a site for the SIP clear of takeoff blast hazards and to prepare a work map of the area to be investigated.

Photographs taken through the LEM window (Sears, 1964) during the inertial descent phase would record more sky than lunar surface. During the constant attitude phase beginning about 115 sec before touchdown, the landing site will be about 7° above the bottom of the LEM window and the horizon about 23°. The pictures may be suitable for locating the LEM, but they would be of little value for mapping and geology.

The most desirable approach from a picture usability standpoint would be to modify the LEM to take photographs with the camera oriented along or near the lunar radius vector. The engineering problems of such modification and an estimate of the extra weight and volume involved are beyond the scope of this contract.

7) Summary

More study is needed on descent camera problems. If it is possible to mount the camera inside the LEM, a problem in itself, off-the-shelf aerial cameras and films can be used to take adequate overlapping pictures down to an altitude of about 1000 ft.

Beginning at an altitude of approximately 800 to 1000 ft, forward motion will virtually cease (NASA, Lunar Flight Handbook, Part 2), and vertical motion will dominate. Pictures taken at the beginning of this descent stage must be sharp, because they can provide material for a photo work map out to a radius of at least 500 ft with a 58.6° lens and to 1000 ft with a 90° to 103° lens.

Camera requirements for sharp, low-blur pictures during descent demand a switch from IMC to faster shutter speeds requiring faster film. Faster film is normally more susceptible to radiation damage.

The critical areas for further study are engineering problems related to mounting the descent camera in the LEM and a detailed analysis of the effects of the low-altitude LEM trajectory on camera and film parameters.

e. Survey Ties to Nearby Surface Features

After the LEM has landed on the moon, and nearby features identified on Orbiter photographs or on film taken during descent, direct survey ties to identified landmarks should be made. Measurements should include distance, bearing relative to the earth, planets, or stars, as well as the difference in elevation. Equipment and procedural details on how these ties may be made are included in the following sections.

3. On-surface Surveying, Mapping and Photography

a. APOLLO Constraints

1) Safety

Safety requirements may change with progress on space suit and LEM testing and as a result of information obtained by unmanned lunar probes. For the purposes of the surveying study the following constraints are assumed:

- Only one astronaut can be out of the LEM at a time.

- The roving astronaut must stay in view of the LEM at all times.
- He must return to the LEM for oxygen refueling within 3 hr after disconnect. The astronaut will have 2 hr for useful scientific work on his first excursion and 2-1/2 hr on subsequent excursions.
- He should stay within a 25 to 30 min walk of the LEM so the suit will have the capacity to sustain him during his return should critical suit control components fail.

2) Manpower

The astronaut remaining inside the LEM will have communication and other duties to perform from time to time. Therefore it is assumed that all survey duties must be handled by the roving astronaut without the other's assistance.

3) Operating Range

The maximum distance the astronaut can traverse from the LEM is probably about 1000 ft.

b. Surveying Measurements, Techniques and Instruments

1) Introduction

Determination of distance, bearing and elevation differences between a surveyed point and a reference point is the objective of a topographic surveying program. For APOLLO the reference point is the LEM. Some of the measurements will be made for accurate location of the LEM relative to features that can be recognized on available photographs or maps and identified on the surface. Most of the measurements will be performed so as to locate sample and observation sites relative to the LEM so that the physical characteristics of the sample sites can be compared with photographic tone, color, texture, pattern, shape, and size of features in the sampled area. Most of the comparative work must be performed by photo interpretation experts on earth.

2) Distance

Distance can be measured by rangefinders, stadia-line intercepts on survey rods, angular intercepts on subtense bars, electronic distance measuring devices, surveying tapes, triangulation, stereo-photography, and pacing.

Stadia intercepts are conventionally read with transit, theodolite and alidade telescopes. Unless these instruments are re-designed, however, the astronaut encased in his space suit will not be able to get his eye close enough to the eyepiece to read accurately and reliably the cross hairs on the stadia rod markings. Also, these instruments are bulky and heavy and will be slow to set up and read under early APOLLO mission constraints. Similar instruments would have to be used for triangulation and for subtense bar measurements, and the objections would also apply.

Distance information can be obtained and recorded using the photo-transit technique described by Jakosky (1960) if it is not necessary to use the distances measured while the astronaut is on the moon. Distance is computed on the film negatives by use of the following expression:

$$D = \frac{f \times k \times R}{i} \tag{3}$$

Where:

D = Distance from transit to target in ft

f = Lens focal length

k = A calibration constant

R = Target separation in ft

i = Target image separation in mm

Accuracy of the distance measured is a function of the distance and the lens focal length. The key parameter measured, i, is read to 4 significant places. Normal stadia accuracy, 1/500 to 1/1000, can be obtained terrestrially with lens choices shown in Table IV-8:

TABLE IV-8

LENS CHARACTERISTICS OF PHOTO TRANSITS

Lens Focal Length	Permissible Rod-Transit Distance in Ft	Vertical View Angle From Film Center (35 mm film)
50 mm	200-250	19.8°
100 mm	400-500	10.3°
200 mm	800-1000	5.0°
400 mm	1600-2000	2.5°

The photo transit described is relatively bulky because it is also used for leveling and to record magnetic bearings. By adding a mil scale to a conventional camera, the distance measuring function could be duplicated.

Adequate stadia markings must be provided for stadia distance surveying. These markings should be targets painted on the side of the LEM (see illustration of targets in Jakosky, 1960, pp. 394-395) that would be illuminated by the sun or by electric lights. If the shaded side of the LEM were not illuminated, it would be difficult for the roving astronaut to see the module against the dark sky.

Optical rangefinders and stereo cameras would not be sufficiently accurate at long ranges. The Hunter's Rangefinder, manufactured by Wild Heerbrugg, Ltd., is a compact device which can be read with an accuracy of 1.9, 20 and 76 ft at ranges of 150, 500 and 1000 ft.

Stereo cameras, however, would be very useful in recording surface detail in the immediate vicinity of the astronaut. A hand-held stereo camera could record distances to details in the immediate vicinity of the astronaut. If equipped with a mil scale, the camera could also record his distance from the LEM with single frame pictures of the LEM stadia markings.

Surveying tape would be useful if the distances measured are in a straight line. Tapes would be too unwieldy for an astronaut pursuing a zigzag course from one sample site to the next.

Terrestrial electronic measuring devices are heavy (80 to 100 lb) and time-consuming to operate. If their accuracy is reduced from one-part-per-million to one-part-per-thousand, it appears possible to reduce the weight to a few pounds by making use of, or redesigning, communication electronics on the LEM and on the roving astronaut.

For electronic ranging, the LEM transmitter would emit an amplitude modulated UHF signal. The astronaut's receiver would detect the signal and in turn modulate and retransmit a second UHF signal back to the LEM.

The detected modulation at the LEM would be compared to the drive modulation and the phase difference would determine the astronaut's range. Range resolution will depend on the frequencies chosen for modulating the transmitters. Choosing λ_m = 6000 ft, the modulation frequency can be established that will yield a 180° phase shift within a 1500 ft astronaut operating range. The frequency would be:

$$f_m = c/\lambda_m = 165 \text{ kc}, \tag{4}$$

Where c = speed of light in ft/sec

Modulating the transmitters near 165 kc will yield a range resolution of : 1500 ft/180° = 8.33 ft/degree of phase shift. If the shift can be measured to 0.1°, the distance would be accurate to about one ft.

3) Bearing

Bearings are normally measured for terrestrial geology with a magnetic compass. Because it is doubtful that the moon has a large enough field to move a compass needle, other techniques should be considered.

A simple compass rose with a center shadow pin and bulls eye level would be useful to record bearing references in pictures of sun lighted areas. If time was recorded when the photograph was taken, the direction of shadow could be used to calculate bearings along structural strikes in the photograph. The shadow length vs pin height would be a measure of the sun's altitude, and the apparent location of the pin on the compass in terms of azimuth and distance of the pin head from center could be used to compute the camera orientation. It would also be helpful if the sun compass had steps of gray or color codes. A schematic drawing of the sun compass is presented in Figure 7, p. V-50.

A gyrocompass would provide a rapid method for obtaining bearings along strike to distant landmarks, or to the LEM from the roving astronaut. The earth could be used as a reference bearing to set the instrument initially and to check gyro precession.

The earth should be a good bearing reference at sites near the lunar limb because its bearing changes relative to lunar north should vary only by libration over a range of about 6° to 7° per 28 days, or about 1/4° per 24 hr. At sites near the center of the lunar disk, however, the earth would be directly overhead and the sightings would not give accurate bearing information.

The earth could be used also as a reference point to turn bearings with a simple peep-sight transit. The transit could be mounted on the multipurpose staff, the peep sight set on a plate angle reading of 360° and aligned with the earth. The sight then could be released and turned to the object being sighted, and the difference in angle recorded. The transit would be lighter and simpler to build than the gyrocompass but would require more time to operate.

If star images could be recorded on film with the image of the LEM, the true bearings of the stars could be computed, and the bearing to the LEM from the astronaut determined. Computations of image sizes, exposures and film-camera resolutions for EG&G 3-layer XR film indicate that time exposures would have to be used to make star images large enough for reliable identification.

Sharp star images were obtained experimentally with a Polaroid Model 110B camera using 3000 ASA film. A 30-sec exposure at f/4.7 was required. On the moon, however, time would be too valuable to use 30-sec exposures and the 3000 ASA film would probably be too susceptible to radiation damage.

The bearing from the LEM to the roving astronaut could be automatically recorded by the TV camera using a directional receiver and positional gyros to track a radio beacon on the roving astronaut. Azimuths would be determined in $1/4°$ or $1/2°$ steps by encoders attached to the servo. This would not require complex encoders, and additional accuracy may be obtainable by observing position of the astronaut relative to the center of the TV screen when angle measurements are received.

If the bearings are taken at the same time as electronic distance measurements, the position of the roving astronaut could be continuously plotted by earth control.

4) Elevation

Terrestrial elevation differences are normally measured by spirit leveling and trigonometric leveling with transits, theodolites, levels, and hand levels. Other techniques involve determining the earth's radius using satellite systems such as SECOR or integrating average inclination angles measured by pendulums in a manner similar to the Johnson Elevation Meter (Speert, 1962).

Because of weight, power and volume problems, the latter techniques do not appear to be applicable to APOLLO. Space suit limitations, such as problems of reading instrument cross hairs, tend to eliminate the rest.

One technique, leveling by photo transit, should be useful. The transit is leveled, and the stadia targets are photographed. Elevation differences are computed by the following formula (Jakosky, 1960).

$$\Delta E = H/i \times R \tag{5}$$

Where:

ΔE = Change in elevation in ft

H = Position of target in mm above or below the 50 mm line (center of film to which instrument level bubble has been adjusted)

i = Difference in mm between top and bottom targets on the film

R = Target separation in ft

The elevation differences could be used to compute (see Table IV-8) vertical angles if necessary. If proper lens-distance combinations are used, the photo transit leveling accuracy is equivalent to about 0.1 sec, far in excess of early APOLLO mission needs.

For most early-mission purposes a level bubble and a mil scale could be mounted on a camera, and pictures taken of the LEM with the camera steadied on the multipurpose staff. The level accuracy would be about 1/4°, or ± 1.1 ft in 250 ft. For gravity surveying, shots longer than 250 ft would require the use of a light tripod to reduce leveling errors to about 4 min (1.2 ft in 1000 ft).

Black and white stadia targets should be painted on the LEM and illuminated with the sun, a flood light or target lights.

The adjustment of the camera levels could be checked by taking pictures of the LEM with the camera leveled on a tripod in the normal and then the reverse position.

A TV camera could also be used but it may be more difficult to adjust and would not have the inherent accuracy of a film camera. Two hundred and eighty TV scan lines would be equivalent to 100 optical line pairs over a stadia target. A 35-mm camera with a camera-film resolution of 40 lines/mm would have 1400 optical line pairs of resolution potential.

5) Summary

TV and film cameras equipped with relatively simple accessories appear to be very useful lunar surveying instruments.

A film camera equipped with a mil scale ahead of the film and level bubbles could be used to measure and record distance and elevation difference relative to stadia targets on the LEM.

The LEM TV camera, mounted on a tracking accessory and used with an electronic ranging device, could measure and transmit the astronaut's bearing and distance from the LEM at all times in addition to full time monitoring of his lunar activities. The TV accessories would weigh about 4.5 lb, 3 on the LEM and 1.5 on the astronaut. Additional power required would be about 10 w, and of this only 200 mw would be required by the roving astronaut. It may be desirable to equip both astronauts with the 1.5-lb ranging package.

Other equipment needed would be a Jacob's staff-ranging pole, a camera tripod if the mission requires gravity measurements, stadia targets on the LEM, a gyro compass, and a simple sun or earth compass for use in the event the gyro failed.

c. Surface Mapping

1) Introduction

Data for a map may be obtained by normal surveying activities, by photogrammetric techniques or by electronic mapping.

Electronic distance measuring devices can be connected with an X-Y plotter to trace the position of the moving system relative to 2 or more fixed installations. These installations appear to be too heavy and too complicated to be used early in the lunar exploration program.

Most early-mission mapping will be done before the astronaut arrives, using orbital photographic data, or after he returns, using survey and photographic data collected on the lunar surface. The astronaut's time will be too valuable to do most routine mapping computations and plotting on the moon. Exceptions could be:

- Preparation of a photo-map from descent photography
- Plotting of X and Y coordinates computed by earth bases from ranging and azimuth data obtained with the TV camera
- Sketching of a few geological details on orbital maps or on descent photographs by the astronaut in the LEM

2) Descent Photography

By using inflight processing, the negatives taken a few seconds before touchdown could provide a detailed map of the landing area. Using these camera parameters from the Itek Day/Night camera (view angle of 58.6°, a 57-mm film format and a film-camera resolution of 30 lines/mm) the minimum altitude, photographic scale and ground coverage per resolvable line, G_{cl}, (see Table IV-9) were computed for operating radii of 500, 1000 and 2000 ft.

TABLE IV-9

MAPPING PARAMETERS USING ITEK DAY/NIGHT CAMERA

Operating Radius	Minimum Altitude	Photographic Scale Ft per In.	Ratio	G_{cl} in Ft per Resolvable Line
500	890	440	1:5280	0.6
1000	1780	880	1:10,560	1.2
2000	3560	1760	1:21,120	2.4

According to data given by Sears (1964), and in the NASA Lunar Flight Handbook, 1963, (Vol. 2, Part 2, p. VIII-45 to VIII-48) pictures at the two higher altitudes listed will not be useful for mapping around the LEM because the forward motion of the LEM will carry the module out of the photographed area. The NASA curves of velocity vs altitude indicate that the LEM forward speed will be zero at an elevation of about 250 to 300 meters, or 820 to 985 ft. These photos should map the operating area out to a range of about 460 to 560 ft to an accuracy of about 0.6 ft per resolvable line pair.

Because some missions may extend to an operating radius of 1000 ft, it will be necessary to use a wider angle camera lens. At an elevation of 800 ft the camera view angle would have to be about 103° to photograph an area 2000 x 2000 ft.

The photograph taken during the hovering and vertical descent period could be printed on a small 10.5 x 10.5 x 6-in. printer using a special 10 x 10 in. format polaroid back, and a 120° enlarging lens. The print could be used to plot short range traverses and as an aid in the selection of a safe area to leave the SIP so that it would be clear of flying debris on takeoff.

The scale could be computed using radar altimeter data taken during descent. Orientation would be a function of the camera alignment with the LEM ground track. If this information were not available, the photographs would have to be scaled and oriented by measuring azimuths and distances to photo features identifiable through the LEM windows.

3) Terrestrial Computing of TV Data

If earth control reduces the bearings and distances obtained during TV tracking of the roving astronaut, the X and Y coordinates of certain key features could be computed and radioed to the astronaut inside the LEM for plotting on simple grid sheets at a scale of about 1 in. = 100 ft. This plot will be useful in planning later excursions from the LEM.

d. Surface Photography

1) TV Camera

The main advantages of using the LEM TV camera on early missions are to:

- Obtain immediate bearing and range information on the roving astronaut by using the TV as part of a tracking and ranging system. His scientific descriptions can be plotted on a map at once by earth control.

- Record data that can be used for time and motion studies. This would be useful in planning subsequent missions.

- Transmit the picture of the area taken by the descent camera.

- Insure his rescue in the event of an accident.

With regard to the latter, if the roving astronaut disappears from sight during a period when the astronaut in the LEM is distracted by communication or other duties, it could be very difficult for the LEM astronaut to locate the man outside. This would be true particularly if the roving astronaut fell into a shaded area or a crevasse which blanked out his line-of-sight radio and visual communication.

If the roving astronaut were watched by earth control and azimuth and range information were recorded continuously to $\pm$ 1 ft and $1/4^{\circ}$, the LEM astronaut could be directed accurately to where the roving man was seen last. At a range of 500 ft this area could be pinpointed to a spot no larger than 2 ft wide and 4 ft long; at 1000 ft the span would be 2 ft wide and 8 ft long.

The lunar TV camera will not have the flexibility and resolution of a film-camera system for recording geologic data. Since it will be restricted by cabling to a 50-ft radius of the LEM, it cannot be taken on most geological traverses.

Resolutions can be compared by computing the elements per unit frame (E. U. F.) using a formula given by Chicago Aerial Industries (1961, p. 20) for each system. If the TV has 280 scan lines on a 1-in. format, and the camera has a 35 mm format with a camera -- (film resolution of 40 lines/mm) the comparisons are:

$$\text{Film Camera: E.U.F.} = (P\ R)^2 \tag{6}$$

Where:

P = Format, 35 mm

N = Resolution in lines per mm, = 40

$$\text{E.U.F.} = (35 \times 40)^2 = 1,960,000$$

$$\text{TV Camera: E.U.F.} = (N/2.8)^2 \tag{7}$$

Where:

N = Number of TV scan lines on 1-in. format

$$\text{E.U.F.} = (280/2.8)^2 = 10,000$$

The computations indicate that a 35 mm film camera should record about 196 times the amount of information recorded by a 1-in., 280-line TV camera. For geologic purposes the extra detail would be extremely valuable.

2) Film Camera

a) Lunar Camera Uses

The lunar hand camera could serve numerous purposes:

- Small-scale features and the geologic setting could be recorded at all sample sites. It would be desirable to take the pictures with a stereo camera, and it may desirable to use both color and black and white film. The pictures must be referenced properly to comments recorded on tape and position-data obtained by the TV tracking equipment.

- The camera could be used to record distance and elevation difference with the addition of a level bubble and a mil scale.

- Photographs of instrument readings, such as gravimeter or magnetometer values, could be taken to be certain no errors are made in reading.

- It may be desirable to obtain photographs of a standard reflectivity target at different sun-camera angles to get a realistic comparison of changes in luminance between the standard target and the lunar surface it is on. Precise requirements for such an experiment necessitate further study.

The camera should be equipped with a level bubble and a mil scale (Jakosky, 1960), to measure elevation difference and distance. This will provide some back-up capability if the electronic distancer does not work.

The camera should be steadied on the multipurpose staff to obtain elevation control to hand-level accuracy, plus or minus 1/4°. Higher accuracy can be obtained by using a light aluminum tripod with a leveling head. The camera lens view axis will be adjusted prior to leaving the launching pad, but could get out of adjustment during takeoff and landing stresses. It will be necessary therefore to check the camera-lens view axis with the horizon as defined by the level bubble. Although there will be no time to make adjustments, the amount of error can be recorded by taking pictures of the LEM target with the camera leveled with the handle in the down position, and again with the handle in the up position. A tripod should be used to insure accuracy. The bubble must therefore be readable in both positions.

Many details of microrelief could be recorded by a stereo camera that would be particularly useful for trafficability studies. Also, small-scale structures in rock exposures, undisturbed surfaces of surficial material and all sample sites could be permanently recorded.

It may be desirable to guard against reading errors by recording gravimeter or magnetometer dial readings on film. This will require fixed camera positioning and standard dial lighting.

b) Lunar Camera Design Problems

The lunar environment creates many camera design problems. Some of the problems and possible solutions classified by environmental area are:

Temperature -- Temperatures on the lunar surface over a 28-day period would vary from about -245° to about +260° F. If the camera lens had to tolerate these extremes, there would be considerable difficulty with differential temperature expansion and contraction binding moving parts, with high temperature film decomposition, changes in film sensitivity, and distortion of camera geometry. Level bubbles used for surveying may boil or freeze, and their adjustments to the camera view axis could be warped. The missions probably will not span the full range of temperatures so the equipment could be designed for specific missions. If the landings occur with the sun about 30° above the horizon, the temperature would approximate terrestrial conditions.

Atmospheric Pressures -- The pressure of the moon's atmosphere is on the order of 10^{-13} torr. At this pressure there could be problems caused by the outgassing of lubricants, film emulsions, plastics, and camera metals. Loss of lubricants could cause seizure by contact welding at bearing surfaces. Loss of gases could fog or alter the film.

Level vials mounted on the camera for surveying purposes may be difficult to seal securely enough to prevent the loss of bubble fluids.

Wright (1963) reported that because of pressure problems many companies recommend sealing and pressurizing the camera interior to about 10^{-2} torr to insure reliability. The level bubbles would be mounted inside the camera, and it may be possible to use gas from a CO_2 cylinder to compensate for slow leaks.

Radiation -- Hazards to the astronaut and to camera film due to radiation have been down-graded in recent studies. Michael et al., (1962), lists the following probable radiation doses inside the film containers:

Radiation Source	Approximate Roentgen Dose
Van Allen protons	0.5
Van Allen electrons	< 0.1
Cosmic rays + secondary radiation	< 0.5
Solar flare (probability of mission occurrence is small)	$>> 1.0$

Effects of radiation include increased film grain size, a higher fog level and a reduced tone contrast. Gamma rays may print a faint radiograph of the surrounding materials on the film. According to Taback (1964) radiation effects are less on slow-speed film emulsions. Reasonably good photographs can be obtained with Kodak SO 243 (1.6 ASA) subjected to 200 rads whereas film with an 80 ASA rating can tolerate only about 3 rads. The film should be carried inside the space ship for shielding from as many radiation effects as possible.

On the basis of radiation dosage levels given by Michael et al., (1962), it was assumed that hand camera film could be returned to earth for developing, without undue risk of radiation fogging, to save weight and time. This risk, however, could be cut approximately in half by developing the film on the moon but this would require more weight and volume for chemical solutions and would probably eliminate the use of multilayer black and white and color film.

Lunar Light Intensity -- According to Hapke (1962) and Halajian (1964) the brightness of lunar objects will depend strongly on the angle between the camera view axis and the sun. The light will be strongly collimated, and the shadows will be very black.

Because of the angle dependence, photographs taken away from the sun with the camera tilted down from the horizontal at the same angle as the sun's elevation may require 1/2 the exposure of pictures taken with the camera pointed at objects on the horizon.

The lunar albedo varies from about 0.05 to 0.13, and the albedo of the LEM, if it is painted a heat-reflecting white, will be about 0.9. If the solar constant is about 13,000-ft candles, and the photographs are taken with the sun about 20° above the horizon, the sun intensity would be 4400-ft candles. The brightness available from lunar albedo conditions in direct sunlight therefore would range from 200 fc to 570 fc and up to 4000 fc when the LEM (0.9 x 4000) is considered.

The luminance variations with shadowing, sun-camera angle changes and albedo variations strongly indicate the desirability of using a film similar to the Edgerton, Germeshausen and Grier XR (Extended Range) film. It obtains an ASA speed range of 400 to 0.004 by combining high, medium and low speed emulsion layers. The film is sensitive to temperatures of more than 75°F and would be difficult to process on the moon should this be necessary.

In addition, the high-speed layer (400 ASA) may be subject to radiation degradation (Taback, 1964). This film could be very useful, however, and should be studied experimentally under simulated lunar conditions. Perhaps a special 3-layer film could be made for lunar operations. For added exposure insurance, Graflex and Kodak personnel suggest using an exposure meter with a very narrow field of view, bore-sighted to the camera view finder. For dependability they suggest using a manual pointer-matching mechanism rather than an automatic lens opening system. Gold (see Appendix A) believes the astronaut should take three exposures of each scene, one with optimum lens opening, another with the exposure 1-f stop high and the third, 1-f stop low.

The luminance in shadows would come from earth light or reflection from the space suit, and may only be 2-or 3-ft candles. Getting details in these areas will require the use of an electronic flash, a flashlight or reflector.

c) Other Problems in Lunar Photography

In addition to lunar environmental problems there are many others related to space suit limitations and to mission requirements. Some of these are:

View and Range Finder -- Conventional view finders will be difficult to use because the astronaut's eye will be at least 3 in. from the camera by the face plate. In addition, it would be difficult for the spacesuit-clad astronaut to hold the camera steady close to his face plate because of the muscular effort required.

Most of the camera companies (Wright, 1964) suggest using a simple gunsight pointer keyed to a field of view marked on the face plate over the astronaut's eye. Such a system would be useful for taking general landscape photographs, but general landscape view of a spot flat enough for landing the LEM will not be particularly useful. What is required are pictures of small features within a few feet of the astronaut.

The gunsight view finder presents serious parallax problems when used to photograph sample sites a few feet from the camera. For this reason a reflex focusing mechanism operating adjacent to or through the lens would be more desirable. A reflex camera is easier to focus than a split image type when held several inches from the eye. A special viewer would have to be built so that the field of view would not be restricted when the camera is held some distance from the face. The design of the view finder will depend in part on where the astronaut would normally hold it for focusing and for maximum steadiness. Elevation differences may be obtained by steadying the camera on the multipurpose staff. Camera procedures should be checked through trial and error by a spacesuit-clad astronaut.

Focusing may be a major problem because the focusing rings could freeze with loss of lubricants in the lunar vacuum. The hand camera must record close-up views of the lunar surface as well as distant shots of the LEM and any landscape forms present. Perhaps focusing can be done in steps with internal lens changes.

Time -- Speed is essential; therefore the camera should be fast, simple and easy to operate. Automatic film advance would save time, and it would be desirable from a speed standpoint to have automatic exposure control. From a reliability standpoint, however, the camera companies do not believe automatic exposure control is desirable. On some missions the film may have to be changed by a space-suited astronaut outside the LEM. It may be necessary in such cases to have the film preloaded in two cassettes to save the time required by the gloved astronaut to thread the film. If the astronaut could hear the camera shutter action in his earphones and also record it on tape, it will be possible to check for shutter-malfunctions and to cross reference the pictures to his verbal descriptions.

Film Capacity -- The camera should have enough film for 2 hr on the first excursion, and 2-1/2 hr on subsequent excursions. Where the camera is passed from one astronaut to the other as they exchange duty stations, it must be possible to change the film in a vacuum.

Normally, 35-mm cameras are used for terrestrial geologic and survey work and should also be satisfactory for lunar use. A lunar camera should parallel the Graflex design for maximum flexibility. It should be possible to take stereo pictures or to take pictures with either lens. This would also allow the astronaut to use two types of film.

A preliminary estimate of the film requirements for a lunar camera on a 2-1/2-hr excursion is:

ACTIVITY		EXPOSURES	
		B&W	Color
Stereo of sample sites		46	46
Record gravity and magnetic readings		20	
Surveying		26	46
Photometric tests		6	6
	TOTAL	98	98

4. Conclusions

a. Surveying

1) Purpose

The primary concern of surveying is to provide bearing, distance and elevation measurements between the LEM and the roving astronaut. Other requirements include dip, strike, thickness, and microrelief measurements on lunar structures. Maps prepared from these data can be used to correlate the astronaut's observations, samples and measurements with lunar photographic characteristics for the extrapolation of the LEM landing area data over wider lunar areas.

2) Instrumentation

Space suit problems, time, weight, and manpower limitations indicate that most terrestrial techniques will not be suitable. Instruments used for early APOLLO surveying must work efficiently under these constraints and provide a working accuracy of about $1/4°$ in bearing, and 1 ft in 500 ft of distance. Surveying instruments recommended include:

- Ranging and bearing device to be used with LEM TV camera
- Level bubbles and mil scale on hand stereo camera
- Gyrocompass
- Stadia targets painted on LEM
- Sun compass
- Jacob's staff-ranging rod

3) Problems and Recommendations

The recommended techniques should be verified under simulated lunar lighting and spacesuit conditions with prototype or modified terrestrial instruments. After verification and any further modification, the instruments should be built to work under the lunar vacuum, temperature and radiation environment.

Considerable progress has been made on building prototype cameras, but these have no provision for accurately aimed, short-range focusing, or level-bubble and mil scale accessories. The TV ranging and bearing devices should take advantage of LEM-astronaut communication circuitry. The gyrocompass will be relatively complex and heavy compared to an earth compass transit, but its potential speed seems to justify its development.

b. Mapping

1) Purpose

The immediate need after landing is a detailed photographic map of the landing area within a radius of 1000 ft for planning traverses. It should be possible to prepare such a map from pictures taken by the descent camera.

After egress, the roving astronaut's position should be plotted regularly for safety reasons and as a guide to sampling.

When the astronauts return to earth with the data collected, mapping will be used to locate sample, measurement and observation sites relative to photographic features to aid in extrapolating this data over larger areas.

2) Instrumentation

Most of the instrumentation is discussed under surveying and photography. In addition to surveying equipment and cameras, computers and technical personnel will be needed at earth control points to decode and plot the digital data from the TV ranging and tracking device. This information should be radioed to the astronaut in the LEM for plotting on a latitude and departure grid with the LEM as origin, and perhaps on a photographic map as well.

Other mapping equipment will include scales, dividers and a photographic projector and printer using Polaroid type printing paper.

3) Problems and Recommendations

Most of the problems involve instruments discussed under surveying and photography. A map of the operating area may be obtained with a descent camera by a photograph taken at the start of the vertical descent phase. This phase apparently starts at an elevation of approximately 1000 ft. Mapping out to a radius of 1000 ft from this altitude will require the use of a wide-angle camera lens with a view angle of at least 90° and larger if the vertical descent phase starts at a lower altitude.

A compact enlarger should be developed that can enlarge the 2-1/4 x 2-1/4-in. negative to a 10 x 10-in. print. Perhaps a special Polaroid pack could be made that would develop the print.

c. Photography

1) Purpose

Lunar photography can record rapidly and accurately the vast amounts of mapping, surveying, geologic, geophysical, and engineering data.

2) Instrumentation

In addition to the LEM TV camera, it is recommended that a 2-1/4 x 2-1/4-in. format aerial descent camera and a dual 35 mm stereo hand camera be carried on early APOLLO missions.

3) Problems and Recommendations

The descent camera film should be processed in the LEM and be available immediately after landing. For this reason and to insure film recovery if the pilot decides against landing, the camera should be mounted in the LEM. From the limited data studied on LEM construction, it may be difficult to obtain satisfactory descent photos with the camera mounted internally without LEM modifications.

Many problems hinge on a precise knowledge of the descent trajectory during the last few seconds of flight from an altitude of about 1000 ft. During this period the camera must be adjusted to switch from image-motion compensation to a faster shutter speed to allow for a nearly vertical descent. The film must be fast enough to allow the shutter to stop motion but slow enough to be reasonably radiation-resistant. The altitude at which horizontal movement stops will also determine the proper view angle of the camera lens for photographing the operating area out to a radius of 1000 ft.

It will not be necessary to develop the hand camera film on the moon unless it is desirable to do so for radiation protection. Data by Michael et al., (1962) indicate that sufficient radiation protection will be obtained by carrying the film in the LEM going to and from the moon. If the film can be developed on earth, it will be practical to use multilayer color and black and white film.

A multilayer black and white film, such as the Edgerton, Germeshausen, and Grier XR film has very desirable exposure characteristics because of the combined low, middle and high-speed emulsion layers. The film needs testing under different radiation levels to evaluate the effects of radiation on the higher speed layers. It may be desirable to develop a special radiation-resistant, multilayer film of this type for lunar usage.

The hand camera should have a level bubble and a mil scale for surveying purposes and provisions for steadying the camera on the multipurpose staff or a light tripod. It should be possible to focus the camera accurately at ranges of 2 or 3 ft to photograph details at sample sites.

Film changes should be possible under vacuum conditions. To enable the astronaut to do this, it may be advisable to pre-thread each film roll in two cassettes. A study should be made to determine if a film change can be made by the astronaut with his hands encased in pressurized gloves and if there would be any adverse effects to the film roll by subjecting it to the lunar vacuum.

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CHAPTER V

ENGINEERING PROBLEMS AND CONSTRAINTS

A. SUMMARY

In previous chapters, the instrumentation state-of-the-art and engineering problems associated with scientific experiments or measurements have been discussed in general terms. This chapter discusses

- Procedures and selection processes in compiling engineering data on instruments and equipment
- General engineering problems associated with measurements and instruments as well as the systems aspect of the scientific instrumentation
- Detailed characteristics of selected instruments and the nature of associated measurement engineering problems
- Components of and design requirements for the unattended scientific instrument package (geophysical observatory or SIP) to be left on the moon

Estimated payload requirements (weight, volume and power) of the optimum selected combination of scientific measurements and experiments are shown to be within the overall constraint guidelines for Alternative I of Flight I when either a battery pack/solar cell array or a radioisotope power supply is used in the SIP. The estimated weight falls slightly outside the 250-lb overall constraint for Alternative II if a secondary battery pack and solar cell array is used.

The weight constraint is met with the radioisotope power supply if the gravity meter is deleted from the recommended instrumentation. For both alternatives, the use of a radioisotope power supply results in a volume distribution problem.

According to these results, a battery pack/solar cell power supply is recommended for Flight I, Alternative I and a radioisotope power supply for Alternative II. Because of the considerably smaller size of the battery/solar cell supply, however, and since the estimated weight difference is felt to be less than the accuracy of the individual estimates, the final choice of power supply type should be left until a detailed design study of the SIP is concluded.

B. COMPILATION OF INSTRUMENT AND EQUIPMENT ENGINEERING DATA

The procedures and selection processes followed in compiling engineering data on instruments and equipment, and the location of the tabulated data in this report, are described in this section.

1. Selection Process

An early step in the conduct of this study was selection of all measurements or experiments which would provide data of scientific and technologic significance relevant to previously identified fundamental lunar problem areas. A comprehensive list was then compiled, by study group, of state-of-the-art instruments and equipment--and those under development--capable of making the selected measurements or experiments which fell within the cognizance of that study group. In this compilation, detailed performance characteristics were not listed, and instruments were rated on a numerical scale with respect to such characteristics as hazards, operating time, reliability, and state of development.

The original lists of measurements and experiments (given in Appendix C) were independently compiled by study groups. After condensing to the most significant of these and eliminating duplications, a final measurement's list was compiled, together with the set of selected instruments and equipment deemed most suitable for these measurements. This latter list appears in Appendix E of this report.

More detailed and specific engineering data on this set of selected instruments and equipment were then assembled. The weight, volume, power, and operating time values used in the analyses of the optimum set of measurements and experiments to be performed on early APOLLO missions were taken from these assembled data.

2. Tabulation of Engineering Data

The comprehensive listing of instruments and equipment is included in this report as Appendix D. At the beginning of the appendix is a list of definitions of the terms used in the tabulations and the rating numbers used in evaluation of the instruments or equipment. The more detailed engineering data on selected instruments appear in Table V-1 of this chapter and in the supplementary discussion following that table. Weight, power, volume, and operating time values included in this tabulation were used in the computer evaluation program to determine the optimum set of experiments and measurements to be performed on early APOLLO missions. The input data to the computer program are presented in matrix form in Appendix F, and the computer program itself is discussed in detail in Part II, Chapter VI, of this report.

Presentation of the more detailed engineering data in tabular form (Table V-1) does not permit adequate discussion of all instruments or items of equipment. Information supplementary to that in the table is provided for a number of the instruments.

C. GENERAL ENGINEERING PROBLEMS

A number of problems related to scientific measurements or experiments on the moon can be discussed in terms of general applicability. These problems are the subject of this section.

1. Restrictions Imposed by Astronaut Capabilities

Each instrument or item of equipment considered for the lunar mission must be evaluated for feasibility of use from the standpoint of the astronaut's limitations or capabilities when clothed in a pressure suit and situated in the lunar environment. Instrument controls must be suitable for manipulation with a gloved hand. It may be difficult or impossible to use optical instruments, such as binoculars or telescopes, with any facility since they can be brought no closer to the eye than the face plate of the suit helmet. It is clear that foot traverse capability will be limited, so only limited separation requirements for placement of instruments can be accommodated. Due to the low lunar gravity, the astronaut will find it difficult to provide sufficient reactive force for such operations as rising, pushing or dragging. Center of gravity considerations and astronaut agility when clothed in the pressure suit will limit the number, weight and bulk of instruments and equipment he can carry during any foot traverse.

A related problem is the hazard to the astronaut involved in the use of any instrument or item of equipment. For example, it will be prudent to protect his pressure suit from damage or puncture by flying rock fragments while using a geologist's pick to obtain rock samples. Thus, a shield must be a concomitant piece of equipment for a geologist's pick. Hazards of individual instruments and experiments are discussed in Section D of this chapter.

2. Compatibility of Output Signal With Data Links

A major portion of the significant data returned to earth on early APOLLO missions will consist of field notes made by the astronauts on their observations and on the results of experiments performed by them. Since manipulation of pencil and notebook will be cumbersome and slow (perhaps even impossible), the bulk of such field notes will be voice-recorded. It has been assumed a voice-modulated radio transceiver will be carried by the outside astronaut for a communications link with the astronaut remaining inside the LEM and with earth. Under these conditions, there will be no need for recording oral notes on board the LEM. However, such considerations as conservation of electrical power and limited information capacity in the earth communication link may make it desirable to record such notes for subsequent transmission at a more suitable time in the mission profile. This procedure would require a recorder on board the LEM, tied in with the earth communication link.

Both the communications between astronauts and the oral notes are likely to be intermittent in nature, i.e., to have a low duty cycle. Optimum use of communication channel capacity, therefore, would seem to dictate recording of such information with an automatic start-stop arrangement on the recorder, with delayed playback and transmission over the communications link.

There is no difficulty anticipated with the radio communication link between the outside astronaut and the LEM because of electrostatic charge on the lunar surface or charged dust particles. In the event of a communication problem, however, a small, portable tape recorder in the astronaut's back pack or pressure suit will be needed for oral notes and measurements. The recorded information then would be played back for transmission on the astronaut's return to the LEM. This latter approach should be avoided if at all possible, since use of a radio communication link with the LEM will involve the least encumbrance and difficulty for the outside astronaut during his traverses.

Most if not all of the instruments listed in the compilation discussed earlier will require some modification of their output signals for the specific data storage and transmission capabilities of the APOLLO system. For some, the data will be telemetered to a LEM-housed tape recorder by a data link separate from that used by the astronaut; in others, output of the instrument will be observed by the astronaut and recorded orally. All instruments selected for the optimum combination recommended in this report are of the latter type, except the tracking transducer on the LEM TV camera, the LEM survey rate meter, the instruments included in the unattended scientific instrument package (SIP), and possibly the reflectance radiometer. It is proposed that the signals from the tracking transducer be telemetered on the same channel as the TV signals. The information rate is low and would not significantly affect the requirements for that channel. The LEM survey rate meter will make measurements during the lunar approach and after landing, prior to egress. A visual output will be provided for observation by the astronauts, but the output signal also should be telemetered to earth. This could be handled over one of the engineering data channels from the LEM. The SIP will have its own telemetry system. If the reflectance radiometer uses filters to obtain spectral data at discrete wavelengths or in bands, a visual output would be monitored by the astronaut. A scanning-type instrument, however, would require telemetry of the output signal.

Where the instrument-LEM telemetry link is required, a buffer storage unit would be necessary preceding the recorder so that maximum advantage could be taken of the recorder's data storage capacity.

Despite the wide variety of instrument types considered in the study, a fairly general statement can be made concerning the necessary conditioning of the instrument output signal to render it suitable for data transmission. A likely approach to the data link between instrument or astronaut and the LEM (or a LEM-housed tape recorder) would be a frequency-modulated RF carrier. Prior to recording for subsequent transmission to earth, this RF carrier will have to be demodulated. Since most of the instruments in their present form have low frequency or d-c analog voltage output or have parallel or serial digital code output, conversion to the FM radio-frequency carrier output must be made and a transmitter built into the instrument. Fortunately, this exacts only small penalties in weight and power for the short transmission distances to be encountered on the lunar surface in early missions. The output signals of those instruments on board the LEM will not require this step but will be used directly to modulate a subcarrier or will be converted to digital form before recording. Because these considerations are so highly dependent on the overall APOLLO systems design and because different approaches to signal conditioning will have such minor effects on weight, power and volume requirements for each instrument, they have not been treated in detail in the instrument engineering evaluation.

3. Power Requirements

Power requirements can be divided into three general classes: (1) power for unattended remote operation; (2) power to be supplied by the fuel cell primary power supply on board the LEM; and (3) power for portable operation. Because the portable instruments will be used on an expendable basis (discarded after accomplishing their intended function), only chemical batteries have been considered for their operation. If repeated use during the mission is indicated, as on multiple excursions, batteries can be of the rechargeable type and can be recharged by the primary power supply. In the case of unattended remote operation, both secondary (rechargeable) batteries with a solar cell array and radioisotope power supplies have been considered, as discussed in detail in Section E of this chapter.

For the computer evaluation program input data, power requirements were converted into equivalent weight and volume for those instruments which would be operated in the portable or remote modes. Instruments to be used on the LEM were listed as requiring power from the primary power supply on board.

4. Scientific Instrument Package

Certain measurements or experiments, to yield significant data, require that the instruments be operated continuously or periodically over longer periods than the astronaut's stay on the lunar surface. Such instruments logically belong in a scientific instrument package (SIP) to be left on the lunar surface to acquire and transmit data to earth by means of a self-contained telemetry system. These instruments and the transmitter will be designed to operate from a common power supply. The additional requirements imposed by the SIP over individual operation of the instruments will be due to the weight and volume of the data storage means, telemetering and control system and the additional batteries (or other self-contained power supply) to permit extended operation. Components and design requirements for the recommended SIP will be discussed in a subsequent section.

5. Lunar Environmental Effects

The APOLLO mission presents a number of new instrument design problems occasioned by the heretofore unencountered operational environment in which the instruments must function. In addition to problems due to the environment itself, there are others posed by the requirement for manned operation in that environment. Inasmuch as the scope of this study does not include detailed instrument design or complete specification of instrumentation requirements, lunar environmental effects on instrument design are not treated in detail. Lehr, Tronolone and Horton (1960) discuss such problems for the space environment. These problems also apply to the lunar environment. The more important environmental factors and their effects on instrument design are discussed below.

a. Micrometeoroid Flux

Meteoroid and micrometeoroid flux are primarily of importance in the design of instruments which will remain on the lunar surface for extended periods of time. Sputtering, erosion and roughening of temperature control and optical surfaces are to be expected. Sealed, pressurized assemblies should be designed with a protective outer shell capable of withstanding micrometeoroid penetration. Another possibility is protection by implantation with dust or rubble covering.

b. Short-Wave Electromagnetic Radiation

Certain materials, particularly organic materials, are affected adversely by ultraviolet or soft X-ray radiation. Materials for external surfaces must be selected for resistance to such degradation. Also, possible secondary radiation from instrument surface materials should be considered both from the standpoint of radiation damage and disturbance of other experiments. The soft X-ray flux appears to be quite low but increases during solar flares.

c. High Vacuum

Effects of the "hard" space vacuum which must be considered in instrument or equipment design include: (1) sublimation or evaporation; (2) removal of surface gas films which affect material properties; (3) corona discharge or arc-over in electrical equipment; (4) electrical leakage or breakdown due to metal whisker growth or to sublimation and redeposition of metals; (5) vacuum or cold-welding phenomena; (6) loss of plasticizers in certain plastics or organics; and (7) chemical reactivity of surfaces due to loss of oxide surface films.

Most of these problems have been met and solved in earth-satellite or interplanetary spacecraft and equipment, and a growing body of information is available to assist in selecting materials and designing equipment to avoid or overcome them. The major difference in previous solutions and those under the APOLLO mission is due to manned operation or installation of the equipment. The most troublesome effects associated with manned operation would appear to be vacuum welding and chemical surface reactivity. All instruments should be tested for problems arising from these effects by operation in a simulated lunar environment and by contact with materials expected to be found on the lunar surface under high vacuum conditions.

d. Temperature Control

Heat transfer to and from instruments in spacecraft is accomplished primarily by radiation and this will be true as well on the lunar surface. In certain cases, however, conduction also will be an important heat transfer mechanism. Careful attention to thermal control will be required on all instruments to maintain temperature within the operating range for the instrument. Design problems will be particularly severe, however, for instrument components of the unattended scientific instrumentation package which desirably would operate through several lunar diurnal temperature cycles.

Three means probably will be employed, either singly or in combination, for thermal control: (1) control of heat absorption and reradiation by means of careful selection of surface materials and design of instrument configuration; (2) control of heat gain or loss by conduction to the lunar surface through appropriate design; and (3) active or thermostatic control by means of feedback-controlled heater elements contained in the instrument package. Since each instrument presents a specific new design problem for thermal control and such design is beyond the scope of this study, a percentage weight and volume factor for thermal control has been used in the analysis to determine the optimum instrument-measurement combinations for early APOLLO missions. Thermal control considerations for the SIP are discussed in a subsequent section of this chapter.

e. Particulate and Gamma Radiation

The major hazard to instruments or equipment due to radiation would occur only during infrequent solar flares. The hazardous components would be high-energy electrons and protons of solar origin and secondary neutron and gamma radiation. Expected flux during a flare is reasonably well known, and instruments or equipment intended for operation over extended periods on the lunar surface need only be designed with adequate built-in shielding or implanted in such a way as to use the shielding properties of lunar surface materials.

f. Lunar Dust

A unique environmental problem is presented by the possible existence and nature of extensive dust deposits on the lunar surface. Dust transport will differ from that observed on earth since there is no atmosphere. There may be charged dust particles in suspension, however, due to electrostatic repulsion. There is also a possibility that particles may become charged by friction due to astronaut motion. If charged dust particles occur, there is likelihood of dust films or layers accumulating on instruments or equipment, as well as the astronaut, due to electrostatic attraction. Such accumulations may affect instrument operation.

Design solutions for these problems prior to obtaining information in an actual lunar landing can come only from experimental work in a simulated lunar environment or from knowledge gained with a successful Surveyor soft landing.

6. Packaging

Weight and volume estimates for individual instruments and equipment items do not include allowance for packaging for the earth-moon flight. Such packaging must provide protection against damage or dislodging during any of the phases of that flight--launch, parking orbit, earth-to-moon transfer, lunar orbit, LEM descent, and LEM landing--and necessarily will result in increased weight and volume. Without a detailed design of all the instruments (which is beyond the scope of this study) it is not possible to determine accurately the payload cost assignable to packaging. Accordingly, arbitrary percentage weight and volume factors were used in estimates of instrumentation payload requirements to allow for the combined payload cost of packaging and thermal control, which was discussed previously. Factors used were 20 per cent in weight and 25 per cent in volume.

Although the design problems are not the same, no good basis was found for using different percentage factors for the SIP and for instruments and equipment which will only be used during the astronaut's stay on the moon's surface.

7. Instrument Location on the LEM

Whether an instrument carries out its function in place on the LEM or is removed by the astronaut subsequent to the lunar landing for use or emplacement on the moon's surface, its location on the LEM is important. In the first situation, considerations which affect choice of location include: (1) the effect of instrument location on measurement accuracy; (2) requirement for operation in the pressurized atmosphere of the LEM; (3) need for accessibility by the astronaut prior to egress from the LEM; and (4) dependence on the LEM primary power supply. For items to be removed after the landing, the dominant considerations are: (1) accessibility and ease of removal by the outside astronaut; and (2) the requirement for composite packaging of the SIP components. Overriding considerations are the available locations and volumes and weights allocable to each.

Preferred location of equipment on the LEM is considered in the detailed discussion of selected instruments in the following section as well as in the optimum instrument/equipment combination chosen for the early flights.

D. ENGINEERING DATA ON SELECTED INSTRUMENTS AND EQUIPMENT

Selected instruments and equipment deemed most suitable for the most significant measurements and experiments are discussed in this section. Engineering data, as detailed and specific as available, are given in Table V-1. For cases in which the tabular form does not permit adequate discussion or description, a supplementary discussion follows the table. Engineering or technical problems associated with the measurement technique are also discussed.

The column headings in Table V-1 are generally self-explanatory. However, brief definitions of some terms used in the table may facilitate interpretation of the data:

Hazards--rated on a 1-5 scale, defined at the beginning of Appendix D. The nature or source of the possible hazard is usually mentioned.

Operating time--total operating time of the instrument for a measurement; not necessarily the same as the time required of the astronaut.

Resolution--the smallest change in the measurand that produces a recognizable change in the instrument output.

Accuracy--static error band of the instrument, usually expressed as per cent of full scale measurand; also, absolute accuracy.

Range--the measurand range, at times called dynamic range, over which the instrument is useful.

Repeatability--the ability of an instrument to reproduce (or repeat) the output signal for repeated application of the input signal.

TABLE V-1

SELECTED INSTRUMENTS AND EQUIPMENT FOR APOLLO SCIENTIFIC MISSION

INSTRUMENT NAME MFR AND/OR INFORMATION SOURCE	MEASURAND OR USE	PERFORMANCE AND OPERATING CHARACTERISTICS	WEIGHT (LBS)	VOLUME (IN^3) DIMENSIONS (IN.)	POWER (WATTS)	SET-UP TIME (MINUTES)	OPERATING TIME (MINUTES)	HAZARDS	ENVIRONMENTAL CHARACTERISTICS	STATE OF DEVELOPMENT	COMMENTS AND SUPPLEMENTARY DATA
1. Permanent Bar Magnet (Alnico) Common Item	Check ferro-magnetism	1 lb pull	0.3	<1 Approx. 4x3/4x1/4	0	0	<1/sample	1	O.K. for lunar use	Commercial item	In sampling package. Used to check for meteorites, similarity between samples
2. Hand Lens Ward's Natural Science Establishment Catalog	Magnification of samples	10 X	0.6	2	0	0	~1/sample	1	Possible UV damage to optics	Commercial item	Should be tested for lunar environment, astronaut's ability to use through helmet faceplate
3. Cooke-MacArthur Petrographic Microscope Rank Organization England	Magnification of samples	10 X to 100 X	2 E	22.5	2 - 1.5 volt batteries	1 E	5 - 15	1	O.K. for lunar use	In development. 6 mos lead time E	Built-in light source. Needs testing for astronaut's ability to use. Requires prepared sample, preferably thin section
4. Jacob's Staff	Depth, penetration, resistance	Telescopic design. Ruled to 0.1 ft, or stadia rod markings	2 E	9 collapsed ~36x5/8 d	0	<1	1 - 5	1	Possible cold-welding problems with telescopic design	Undeveloped	Used to probe dust thickness, lend stability to astronaut, as stadia rod. Accessory: dial gauge penetrometer.
5. Gyro Compass w/Inclinometer Astro-Space Laboratories	Azimuth relative to base line, dip angle	Accuracy ~ 1^{o}. Circular scale readout	3	22	5	<5	1/meas.	1	U	Prototype. Needs mod. for sight, inclinometer	Needs test lunar environment
6. Inclinometer Keuffel & Esser	Dip angle	1 - 2^{o} accuracy. Pendulum type. Circular scale readout	0.5 E	10 E	0	<1	1/meas.	1	U	Commercial item. Needs modification. 3-6 mos lead time E	Pivot bearing must be sealed for vacuum
7. Maps, Topographic and Photogeologic	Landing site location	1:25,000 scale. Min. resolution: 85 ft horiz, 15 ft vert	0.1 E	2 E	0	N.A.	N.A.	1	Must be packaged for lunar environment	Undeveloped	To be prepared from Ranger, Lunar Orbiter photographs. Probably sealed in plastic for ease of handling
8. Erosion Particle Movement Sampler	Passive dust particle collection	Collects representative sample of near-surface dust particle movement	1 E	35 E folded	0	10 E incl. retrieval	U	1	Possible cold-welding problems w/folding design	Undeveloped 1-2 mos lead time E	Conceptual instrument: simple pan and sandwich baffle w/folding arm to change baffle height
9. Hardness Points Ward's Natural Science Establishment Catalog	Rock hardness	Range: 5, 6, 6.5, 7, 7.5, 8, 9, 10 on Moh scale	0.3	5	0	0	1-2/meas.	1	No difficulties foreseen for lunar environment	Commercial item	Could be replaced by knife and other items in astronaut's equipment, suitably chosen for relative hardness
10. Comparison Charts American Geophysical Inst.	Color, grain size, percentage estimate	Sealed in plastic, used for visual comparison-estimate	0.6 E	4 E	0	0	1/meas.	1	Package for lunar environment	Developed, need modification	AGI data sheets 1 to 13, 15, 16 and others: (grain size, percentage estimate, etc.). GSA color chart
11. X-Ray Diffractometer (Weber, 1963)	Mineral composition	Output: count rate, voltage pulses. Peak width, 1/2 height: 0.205^{o}. Scan range: 7-90^{o} (2θ). Peak intensity reproducibility: 1% avg.	17.6	1200 E	60	15 E	20 - 160 scan	2 high voltage, X-rays	Approval testing for Surveyor in progress	Prototype developed for Surveyor. Modifications desirable	Requires prepared sample. Modification to use lunar surface as sample desirable. May increase size, weight. 1 - 2 yr lead time E
12. IR Spectrometer (Weber, 1963)	Mineral, gas composition	Simple grating spectrometer w/front surface mirror. Output: analog voltage	2 E	40 E	<5 E	5 - 15 E	15/anal E	1	U	Undeveloped. 1 - 3 yr lead time E	Primarily used for liquids, gases. Recent work on mineral reflectance, absorption, luminescence. Breadboard planetary unit, Univ. Manchester

TABLE V-1 (CONTD)

SELECTED INSTRUMENTS AND EQUIPMENT FOR APOLLO SCIENTIFIC MISSION

INSTRUMENT NAME MFR AND/OR INFORMATION SOURCE	MEASURAND OR USE	PERFORMANCE AND OPERATING CHARACTERISTICS	WEIGHT (LBS)	VOLUME (IN^3) DIMENSIONS (IN)	POWER (WATTS)	SET-UP TIME (MINUTES)	OPERATING TIME (MINUTES)	HAZARDS	ENVIRONMENTAL CHARACTERISTICS	STATE OF DEVELOPMENT	COMMENTS AND SUPPLEMENTARY DATA
13. Differential Thermal Analysis (Gordon, 1960)	Mineral composition	Output: analog voltage prop. ΔT sample-to-reference material. Thermocouple sensors, millivolt levels	10 E	860 E	200 E	10 - 15	15 - 30/anal	1	Heat transfer and control likely problems	Commercial lab item. Lunar model undeveloped	Sample, ref temp varied at selected rate. Norm. used in air atmosphere - vacuum use may present severe problems
14. X-Ray Spectrometer (Weber, 1963)	Chemical composition (solid)	Outputs: voltage pulses, count rate, 13 channels, plus 1 pulse height analyzer output. Sensitivity 0.1 - 1%	33 E	360 E	25 E	5 - 15	15 - 30/anal	2 high voltage X-rays	Undergoing tests for Surveyor I	Surveyor I instrument - Philips - JPL 1-2 yr to modify	First unit had developmental problems. Requires prepared sample - mod. to use lunar surface desirable
15. UV-Visible Absorption Spectrometer (Anon., Av. Week, 1961)	Chemical composition, life forms	Output: analog voltage. Range: 210 - 600 mμ. Resolution: 0.02 mμ, photometric accuracy ± 0.1 to 0.25%	12	1700 approx. 22 x 8 x9	4	5 - 15	10/scan	2 solar furnace	Designed for lunar environment	Prototype built for Surveyor - Beckman Instruments	Dual beam ratio system, auto-scan. Requires 5 gm sample, ground 100 mesh. Solar furnace (Fresnel lens) vaporizes sample
16. UV - Visible Spectrometer (Weber, 1963)	UV-visible radiation, reflectance	Output: analog voltage (PM tube), Range: 200-600 mμ, Resolution: ~10 mμ @ 200 mμ	2 E	50 E	neg.	5 - 15	5 - 15/scan	1	"	Prototype, AVCO Corp.	Grating monochromator, auto-scan. Could be used as absorption spectrometer w/addition solar furnace, sample holder
17. Neutron Activation Analyzer (Weber, 1963)	Chemical, stable isotope composition	Coded output from 96 channel pulse height analyzer. Detector resolution 9% @ 0.633 Mev. Neutron source: 10^4 n/pulse, 10^3 pps	22	1700 E	100	5 - 15	15 - 30/anal	2 high voltage, neutrons	"	Prototype for Surveyor. Needs improvement. 2-3 yr lead time E	Collaboration by JPL, LRL, Aerospace Corp., Sandia, UC Space Science Lab. Needs stronger neutron source, 256 channel PHA
18. Alpha Scattering Spectrometer (Weber, 1963)	Chemical composition (solid)	Coded output from 2 - 128 channel pulse height analyzers. Resolves adjacent elements to amu 40(Ca). Detects ~1 atom %	8	500 E	1.4	5 - 15	5/anal E	2	"	Surveyor breadboard prototype. Lead time 1 - 2 yr E	Prof. Turkevich, Univ. Chicago. Requires sample prep.; use of lunar surface as sample desirable
19. Neutron Scattering (Johnson, 1962)	Chemical composition (solid)	5 decade scaler output. Uses 5 millicurie neutron source of Ra^{226}-Be, spring-wound timer	30 E	860 E	3 E	5 - 10 E	5 - 15 E	2 neutrons	Needs design for space use	Portable field inst. Needs mod. Lead time 1 - 2 yr E	W-V-P estimates are for lunar model. Shielding requirements may increase these
20. Gas Chromatograph (Wilhite, 1963)	Chemical composition (gas, solid), life forms	Analog output voltage, dynamic range $\sim 10^4$; $\sim \pm$ 6% accuracy; resolution $3x10^{-10}$ mole	13.2 E	690 E	15 (avg) 24 w-hr/anal	5 - 15 E	100/anal		Oper. range -30 to 100°C. Designed for lunar use	Surveyor I design. Lead time 1 yr E to mod. for Apollo	Will separate, identify 28 constituents, incl. CO, CO_2, NH_3, H_2O, O_2, N_2, organics
21. Mass Spectrometer (Schrader, 1962)	Chemical, stable isotope comp., life forms	Analog output voltage 0 - 5 v, 7 channels + total current. Masses 1, 4, 14, 16, 18, 28, 32	23	700	27	5 - 15 E	64 sec/scan	1	Designed for Satellite S-6	Space model - Consolidated Sys. Corp. Lead time 1-2 yr E	Built for Goddard SFC. Sensitivity inadequate for Apollo. Weight, size could be reduced. Magnetic focusing
22. Mass Spectrometer (Brubaker, 1963)	"	Output: pulse count. Scan control by d-c voltage, amu 2 to 50°, Resolution 10^{-12} torr. Dyn. range: 10^6	15 E	860 E	27	5 - 15 E	1-5/scan	1	U	Undeveloped - considered possible. Lead time 2-3 yr E	Quadrupole mass filter (possibly time-of-flight). Heated filament proposed to vaporize sample.
23. Gamma Ray Spectrometer (Weber, 1963)	Chemical, radio-isotope composition	Coded output from 32-channel pulse height analyzer, 16 bits/chan. Detect 0.08% K^{40}	12	860	<1.5	5 - 15 E	5 - 15 E	2 high voltage γ-rays	Space environment	Ranger III, IV, V instrument. Lead time to improve 1-2 yr E	Proposed, designed Los Alamos, UC at La Jolla, JPL. This type instrument part of 17. Needs mod. for Apollo. 256 channel PHA suggested
24. Alpha Ray Spectrometer	Chemical, radio-isotope composition	Coded output from 128 channel pulse height analyzer	4 E	430 E	1.4	5 E	5 - 10 E	1	Lunar environment	Part of Surveyor breadboard prototype. Lead time 1-2 yr E	Uses detector, pulse height analyzer from alpha scattering spectrometer (Item 18)

TABLE V-1 (CONTD)

SELECTED INSTRUMENTS AND EQUIPMENT FOR APOLLO SCIENTIFIC MISSION

INSTRUMENT NAME MFR AND/OR INFORMATION SOURCE	MEASURAND OR USE	PERFORMANCE AND OPERATING CHARACTERISTICS	WEIGHT (LBS)	VOLUME (IN^3) DIMENSIONS (IN.)	POWER (WATTS)	SET-UP TIME (MINUTES)	OPERATING TIME (MINUTES)	HAZARDS	ENVIRONMENTAL CHARACTERISTICS	STATE OF DEVELOPMENT	COMMENTS AND SUPPLEMENTARY DATA
25. Gamma Ray Backscattering (Canup, 1962)	Rock, soil density	Output: voltage pulse count rate. Linear range: 0.2 to 4 gm/cm^3. Accuracy: ± 0.1 gm/cm^3 on consol. materials	Probe: 3.2 Scaler: 6 E	750 E	Probe: 0.01 avg. Peak: 250 for 0.5 sec	5 - 10 E	5 - 10 E	2 γ-rays	Designed for lunar environment	Surveyor I instrument. Lead time 1 yr E to modify	Probably best suited for density profiling. Designed, built by Texaco Experiment, Inc., for JPL, Contract No. 950115
26. Kreisman Vacuum Gauge Vacuum Industries Inc.	Atmospheric pressure	Range: 10^{-4} to 10^{-14} torr. Uses Ni^{63} trigger. Output: 2 amp/torr to 10^{-10} torr, converted to linear or log voltage	Gage: 1.25 Elect: 5 E	85 E	8 (4 kv, 2 ma)	5 E	5 - 10 E	2 high voltage	U	Commercial item. Space model in devel Lead time 1 yr E	Developed under NASA Contract No. NAS 5-270. W-V-P estimates for space model
27. Sample Culture w/pH Readout (Anon.,C & E News, 1964)	Life form detection	Output: analog voltage, 0-5 v-dc. Resolution adequate, repeatability ± 0.2 pH units	1.2	28	1.3	NA (return trip)	5 E	1	LEM interior	Space probe systems in development. Lead time 1-2 yr E	Readout unit by Beckman Inst. No external radiation interference w/this detection scheme
28. Sample Culture w/Radioisotope Readout (Levin, 1962)	Life form detection	Output: voltage pulse count rate. Resolution adequate, repeatability ± 50 - 100 cpm	1.5	1600	0.25	"	5 E	2	LEM interior	"Gulliver" Mars experiment. Lead time 1 -2 yr E	Sample collection scheme mod. for Apollo. Possible external radiation interference
29. Solar Plasma Spectrometer (Weber, 1963)	Flux, energy of charged particles	Output: analog voltage ∝ log current, 8 decades. Measures low energy particles (electrons, protons, heavy positive ions)	10 E	400 E	< 0.5	5 E	Desirable over lunar diurnal period(s)	1	Magnetic field at sensors must be < 10^{-3} gauss. Oper. temp, 0-70°C	Ranger, Surveyor, Satellites(Instruments). Lead time 1 yr E	Neugebauer electrostatic velocity selector or Rossi probe. Estimates for array of 6. One set (2 probes) aligned ±5° of moon-sun line
30. Survey Rate Meter (Neher, 1953)	Ionizing dose rate	Range: 3.4 x (10^2 to 10^7) ion pairs/cm-sec of air. Protons: 10 Mev. Electrons: 0.5 Mev. ± 1% accuracy. 10^{-10} coul/count	1 E	70 E	0.1	5 E	1 - 5 or lunar diurnal period(s)	1	Space environment	Mariner II instrument. Needs visual rate output. Lead time 1 yr	Integrating ionization chamber
31. Particle Spectrometer (Fisher, 1963)	Electron, proton flux, energy	Coded binary output (3-16 channel PHA's) plus 0-5 v log rate (3 channels). Protons: 10-130 Mev. Electrons: 0.05-1 Mev	11	200 E	2	5 E	"	1	Space environment	New design of this inst. for Gemini. Lead time 1 yr E	Uses scintillators, photomultiplier tubes, 2 CsI Xtals in proton telescope, 1 in electron telescope
32. Portable Survey Rate Meter (Rowland, 1964)	Ionizing dose rate	0-5 v analog rate output, plus scaler memory integrated by 10 point commutator. Range to 10^5 pulses/sec. Set for 1 Mev electrons	2	60 E	0.09	5 E	5 E	1	Space environment	New design for Gemini. Lead time 6 mos - 1 yr E	Scintillator and photomultiplier tube, CsI crystal. Designed for 2π ster solid angle. Directional capability desirable
33. Chemical Reactivity Detectors A.D. Little	Reactivity with lunar surface material	Thermocouple or resistance thermometer bridge output	0.5 E	0.02 E	17 E	5 E	5 - 10 E	1	No difficulties foreseen, lunar environment	Conceptual. Lead time 1 yr E, develop, test	Small samples pressure suit, equipment materials, instrumented to measure temp rise. Drop to surface before LEM egress
34. Personal Dosimeter Landsverk Electrometer Co	Cumulative radiative dose	20 kev to 1.4 Mev range. Field scale range 0.2 to 50 R R.A.S. to 1000 R. 4 mr/day discharge rate. Accuracy ± 2%	0.3 E	0	1	0	0	1	Needs sealing for vacuum environment	Commercial item. Lead time to modify, 6 mos E	Charge to 180 v at mission start. Optics need mod. for astronaut use
35. Meteoroid and Lunar Ejecta Detector A.D. Little	Flux, trajectory, momentum of particles	Coded scaler output, 4 channels, plus voltage pulses or pulse height analyzer output from 3-channel microphone or displacement sensor	20 E	1700	1 E	5 - 15 E	Desirable over lunar diurnal period(s)	1	U	Conceptual design by A.D. Little. Lead time 1-3 yr E	Two concentric hemispheric capacitor sheets, sectored, backed by momentum absorber w/3 orthogonal displacement sensors
36. Meteoroid and Lunar Ejecta Detector (Weber, 1963)	Flux, velocity, momentum of particles	Coded scaler (or timer) output, 2 channels, plus pulses from 2 acoustic detectors	11	1150	0.4	5 - 15 E	"	1	(Tested @ 77°K & 130°C.) Acoustic detector qualified Ranger PTM	Designed for Surveyor. Lead time 6 mos - 1 yr E	Goddard SFC and J.L. Bohn, Temple Univ. Capacitor sheets developed for EGO, POGO, Mariner B

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37. Susceptibility Bridge (modified Moonev-type) (Canup, 1962)	Magnetic susceptibility (surface)	Output: analog voltage. Range: 100,000 x 10^{-6} cgs units. Resolution: 2 x 10^{-6} cgs units	0.6	17	0.06	5 E	5 E	1	Tested for Surveyor	Surveyor I development instr. Lead time to modify 6 mos to 1 yr E	Induction balance system. Developed by Texaco Experiment Inc. for JPL. Also gives conductivity information from phase output signal
38. Fluxgate Magnetometer (Wyckoff, 1962)	Magnetic field, 3 axes	2 ranges: 0 to ± 64γ, 0 to ± 320 γ. Noise equiv: 0.25γ. Resolution, low range: 0.6γ	4.6	U	6	5 - 15	Desirable over lunar diurnal period	1	Space probe model	Mariner II instrument. Lead time to modify, 6 mos to 1 yr E	Flown on Mariner II
39. Low-Field Helium Magnetometer Texas Instruments	Magnetic field 3 axes	Output: 0 - 7 v dc analog (3-axis). Range: ± 364 γ. Resolution: 0.5 γ. Passband: 0 - 1 cps	6.15	257	7	5 - 15	Desirable over lunar diurnal period(s)	1	Sensor: -50 to +55°C. Electronics: -20 to +65°C. Tested for launch env	Developed for Satellite flight. Lead time to modify 6 mos - 1 yr E	JPL Contract No. 950355
40. Electrodes, Voltmeter, Cables, Current Source	Resistivity, spontaneous polariz.	Current source: ac/dc, pulse. Voltmeter: high impedance, 250/1000 mv ranges. Electrodes: non-polarizing	Electrode-Cable: 2 ea E. Electronics: 6 E	Electrode-Cable: 40 ea E. Electronics: 220 E	Current source: 200. Voltmeter <1 E	15 E	5 - 15 E	1	U	Commercial items. Need modification. Lead time 1-2 yr E	Two electrodes, voltmeter for spontaneous polarization. Contact resistance difficult problem. W-V-P estimates for lunar model
41. Charged Dust Detector (Weber, 1963)	Charged particle flux	Analog voltage output, ∝ log current. DC potential control of velocity selector	2 E	60 E	< 0.5	5 - 15 E	Desirable over several hours	1	Oper temp range 0 to 70°C	Undeveloped. Lead time 1 - 2 yr E	Similar to solar plasma spectrometer based on Neugebauer electrostatic velocity selector. Cannot separate speed, charge/mass ratio
42. Tidal Gravity Meter	Gravitational acceleration	Electronic null, analog voltage output. Range: 4 milligal Resolution: ±0.02 milligal	33 E	1900 E	1 E	5 E	Desirable over lunar diurnal periods	1	U	Undeveloped. Proposed mod. of commercial item. Lead time 1 yr E	Proposed adaptation of LaCoste & Romberg tidal gravimeter
43. Quartz Gravity Meter	"	Electronic null, dial readout. Range: 12,000 milligal. Resolution: 0.1 milligal	7 E	450 E	<1	1 - 3 E	1/meas. E	1	Temp range: 0 to 50°C	Commercial item, proposed mod. Lead time 1 yr E	Feasibility established, proposed development by Texas Instruments to MSC. Concomitant measure rel. elevation observ. points needed
44. Gradiometer (vertical)	Gravitational acceleration gradient	Readout: optical scale or optical null w/dial readout. Range: 80-200 Eötvös. Resolution: 1 Eötvös	5 E	430 E	<1	5	U	1	Temp range: 0 to 50°C	Undeveloped. Lead time 1 - 2 yr E	Feasibility established using two quartz gravity meters. Does not require concomitant measure of elevation
45. Lunar Seismometer Lamont Geophys. Lab.	LP and SP seismics, tidal gravity	Short period: 1.25 mv/mμ, 0.05 to 10 cps range; long period: 0.25 mv/mμ, 0.016 to 1 cps range. Both 30 db (compressed to 20 db)	32 E	1500 E	0.65 (2 peak for heater)	5 - 15	Desirable over lunar diurnal periods	1	Temp control desirable to ± 20° C	Surveyor instrument. Lead time to modify 1 - 2 yr E	Prototype developed under Contract NASw-82 & JPL 590157 Feedback loop for LP seis gives tidal gravity. LP seis, 3-axis; SP seis vertical only
46. Jakosky Torsion Balance	Gravitational acceleration gradient	Optical scale readout. Range: 100 Eötvös. Resolution: 1 Eötvös	50	7000	1	5	60	1	Terrestrial ranges	Undeveloped. Lead time 1 yr E	Does not require concomitant elevation measurement. Development dormant for about 30 yr
47. Long-Period Seismometer (Kovach et al., 1963)	Long-period seismic noise	Output: analog voltage; mag. 10^4 @ 20 sec period. Freq range: 0.01 to 5 cps. Dynamic range: 30 db, compressed to 20 db	10 E	600	1 E	5	Desirable over lunar diurnal period(s)	1	Designed for lunar environment	Prototype developed for Surveyor. Lead time 6 mos - 1 yr E	3-axis unit. Developed under Contract NAS 7-100, Seismol. Lab., C.I.T., for JPL
48. Short-Period Seismometer (vertical) (Lehner et al., 1962)	Short-period seismic noise	Analog output voltage: 0.8 μv/mμ @ 1 cps; Freq range: 0.05 to 5 cps. Range: 30 db (compressed to 20 db)	8 E	86	1 E	10	Desirable over extended period	1	Lunar environment	Ranger III, IV, V instrument. Lead time to modify 6 mos to 1 yr	Designed for hard landing. Vertical axis only. Developed by Seismological Lab., C.I.T., for JPL, Contract NASw-81

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49. Portable Refraction Seismic System (Kovach et al., 1963)	Induced seismic motion	Analog output voltage. Range: 20 db. Resolution: 10 mμ. Freq. response: 10 to 100 cps E	12	600 E	12	20	1	2 (explosives)	Designed for lunar environment	Prototype unit Lead time 6 mos to 1 yr E	Designed for astronaut use by Seismological Lab, C.I.T. Deploys explosive array over ~2000 ft base line. W-V of source not included
50. Landing Gear Thermometer (resistance type) Rosemount, Inc.	Landing gear temperature	Analog voltage, resistance bridge output Resolution: 0.01°C. Accuracy: ±0.1°C (calibrated). Range: -260°C to +500°C	0.5 E	4 E	0.015 (30 v)	0	2 E	1	Bridge unit: temp range, -150 to +150°C Zero shift: 0.002°C/°C	Commercial item. Adaptation lead time 6 mos E	Platinum resistance element in precision resistance bridge. Ties in with planned LEM system
51. Landing Gear Thermometer (thermocouple) Con-Ohmic	"	Analog voltage, millivolt range. Resolution: 0.1°C. Accuracy: ± 0 1°C (calibrated). Range: -200°C to +400°C	0.5 E	4 E	0.15 mw (0.4 v)	0	2 E	1	Reference junction unit: -40 to 100°C; drift, 0.06°C/°C	Commercial item. Adaptation lead time 6 mos E	Copper-constantan thermocouple w/solid-state reference junction temperature control. Probably also ties in w/LEM system
52. Boot Thermometer (Cu-Constantan Thermocouple) Rosemount, Inc.	Boot temperature	Analog voltage, 37μv/°C. Range: -200°C to +500°C. Resolution (w/meter): ≈10°C. Accuracy: ± 1 - 2%	0.5 E	4 E	0	0	2 (total)	1	Reference junction: -40 to +100°C; drift, 0.06°C/°C	Commercial item. Adaptation lead time 6 mos E	Solid-state reference junction temperature control, millivoltmeter series circuit. Estimated time for total of period observations
53. Boot Thermometer (resistance type) Rosemount, Inc.	"	Analog voltage, resistance bridge output. Resolution (w/meter): ≈10°C. Accuracy: ±1-2%. Range: -200 to +500°C. Available R: 10^2 to 10^3 Ω	0.5 E	4 E	0.02 E (10 v)	0	2 (total)	1	Bridge unit: temp range, -150 to +150°C Zero shift, 0.002°C/°C	Commercial item. Adaptation lead time 6 mos E	Platinum resistance element sensor in precision resistance bridge, voltmeter readout. Requires more power (battery) than 52
54. Platinum Resistance Loop Rosemount, Inc.	Surface temperature	Analog voltage, resistance bridge output Resolution: 0.5°C. Accuracy: ±0.4%. Range: -200 to 400°C. Loop 10 ft diam., 20 Ω resistance	0.2	2	0.015 E (30 v)	12	Desirable over lunar diurnal period(s)	1	Bridge unit: temp range, -150 to +150°C; drift, 0.01 °C/°C	Adaptation of commercial item. Lead time 6 mos E	Careful emplacement w/minimal surface disturbance required. Good temperature averaging
55. Thermocouple Loop Con-Ohmic	Surface temperature	Analog voltage, millivolt range. Range: -260 to +400°C. Resolution: 0.5°C. Accuracy: ± 0.4%	0.2	2	0.15mw (0.4 v)	12	"	1	Reference junction unit: temp range, -40 to +150°C; drift, 0.1 °C/°C	Adaptation of commercial item. Lead time 6 mos E	Series of thermocouple junctions for temperature averaging. Reference junction unit has self-contained battery, could be supplied externally
56. Thermal Conductivity Probe (thermocouple) Custom Scientific Inst A. D. Little	Thermal conductivity, temp. (subsurface)	Analog voltage, slow transient. Range: $2x10^{-6}$ to 1 watt/cm-°C. Estimated accuracy: ±10%. Estimated resolution: ±3%	0.4	4	0.01 to 1.0	5 - 15	30 - 60	1	Temp range: probe, -150 to +150°C; ref. jctn, -40 to +100°C	Modification of commercial item, 6 mos to 1 yr E	Heater coil and temperature sensors; measure rate of temperature rise due to applied heat. Various types. Drift, ref. jctn, 0.06 °C/°C
57. Thermal Conductivity Probe (thermistor)	"	Analog voltage, slow transient, resistance bridge output. Range: $2x10^{-6}$ to 1 watt/cm-°C. Resolution: ±3% E. Accuracy: ±10% E	0.4	4	0.01 to 1.0	5 - 15	30 - 60	1	Temp. range: probe, bridge unit, -150 to +150°C	Modification of commercial item, 6 mos to 1 yr E	Same as 57, w/thermistors replacing thermocouples. Drift, bridge unit, 0.01 °C/°C
58. Modified Flash Radiometer	Thermal diffusivity (surface)	Analog voltage transient. Range: $3x10^{-6}$ to 2 cm^2/sec. Resolution: 5% E. Accuracy: ± 10% E	5	1700	U	15 - 30	60 E	1	U	Undeveloped - conceptual instrument. Lead time 1 yr E	Progression of heat wave due to flashed radiation monitored by array of IR detectors focused on lunar surface
59. Reflectance Radiometer (UV, visible, IR)	Surface emittance reflectance	Analog voltage output. Resolution: 10% E. Accuracy: ± 20% E	5 E	100 E	1 E	15 - 30	60 E	1	U (probably large)	Undeveloped - conceptual instrument. Lead time 1 yr E	Radiation detectors monitor reflected & emitted radiation from surface, probably using incident solar energy as source. Spectral info. requir
60. Heat Flow Meter (modified) National Instrument Labs Beckman - Whitley	Heat flow (surface)	Analog voltage output, millivolt range. Range: 10^{-4} to 1 watt/cm^2. Resolution: 3%E. Accuracy: 5 - 10%	0.7 E	12 E	0.02	15 E	> 60	1	Temp range: -150 to 100°C. Temp coeff: ≈0.3%/°C	Commercial item, modified Lead time 6 mos E	Conductive type: thin disk w/multiple thermocouple assembly to measure ΔT across disk Requires burying in surface; emplacement may cause errors

TABLE V-1 (CONTD)

SELECTED INSTRUMENTS AND EQUIPMENT FOR APOLLO SCIENTIFIC MISSION

INSTRUMENT NAME MFR AND/OR INFORMATION SOURCE	MEASURAND OR USE	PERFORMANCE AND OPERATING CHARACTERISTICS	WEIGHT (LBS)	VOLUME (IN^3) DIMENSIONS (IN.)	POWER (WATTS)	SET-UP TIME (MINUTES)	OPERATING TIME (MINUTES)	HAZARDS	ENVIRONMENTAL CHARACTERISTICS	STATE OF DEVELOPMENT	COMMENTS AND SUPPLEMENTARY DATA
61. Radiometric Heat Flow Meter A.D. Little	Heat flow (surface)	Analog voltage output, millivolt range. Range: 10^{-4} to 1 watt/cm^2. Resolution: 5% E. Accuracy: 10% E	0.7 E	12 E	0.01	15 E	> 60	1	Temp range: -150 to +100°C Ref junction temp drift: 0.00 °C/°C	Conceptual instrument. Lead time 6 mos to 1 yr E	Blackened disk suspended above lunar surface, temperature of disk monitored. Also use 60, monitor temperature and ΔT
62. Line Source Pressure Gauge A.D. Little	Interstitial gas pressures	Analog voltage, slow transient. Range: 10^{-4} to 100 torr (several sensors required to cover span). Resolution 10% E. Accuracy: 30% E	1.5	15	0.1	15 - 60	> 60	1	Temp range: probe, -150 to +150°C; reference junction, -40 to +100°C	Commercial item, modified Lead time 6 mos to 1 yr E	Measures thermal conductivity of standard reference powder material in pressure equilibrium with lunar surface material. Similar to 57
63. Theodolite (w/tripod) T-12 Wild Heerbrugg, Ltd	Bearings, vertical angle, distance	Resolution, accuracy: ± 2 min vertical, ± 1 min horiz. Mag.: 5X. Field diam @ 1000 ft: 140 ft	6.6	Theod. 50 Tripod 690 E	0	5 E	10 E	1	Temp range: -40 to 120°F. Bubble level may boil, freeze	Commercial instrument. Lead time to modify 1 yr E	New design of tripod might reduce volume. Bearings need mod. for vacuum
64. Tracking Transducer on LEM TV Camera	Distance, azimuth to astronaut	Output: digital code for azimuth, 1/2° accuracy; phase detector output for range. Range resolution depends on freq. used, 1-4 ft E	4.5	150	10	0	0	1	Temp range: -50 to +125°C E	Conceptual instrument. Lead time to develop 6 mos to 1 yr	UHF Rcvr-Xmitter carried by astronaut, UHF Xmitter-directional Rcvr on TV camera Setup time included in TV camera setup
65. Photo-transit (w/tripod) (Bazhaw, 1964)	Bearings, elevation difference, distance	Output: film recording of angles, stadia target image. Angular accuracy: ~ 6 min. Distance 1 ft/500 ft. Magnetic bearings to 1/4°	15	Transit 2600 Tripod 690 E	<1	2 - 5 E	1-2/ meas.	1	Temp range: -40 to +120°F. Needs mod. for vacuum, level device	Commercial item. Lead time to modify 1 yr E	Records image of stadia rod, angle plate, landscape objects from which surveying info can be subsequently calculated
66. Sun Compass	Sun altitude, orientation of camera, photo.	Shadow pin on levelled compass rose gives sun direction altitude. Grey and color scales provide comparative standards	0.3	3	0	< 0.5	0	1	Levelling device must be designed for lunar environment	Conceptual accessory. Lead time to develop 6 mos E	Used to orient geologic features in photograph relative to sun. Pin mounted vertically in center of comp.rose. Part of astronaut's geol kit
67. Night Stadia Targets on LEM	Distance	Intercept interval of target patterns on camera mil scale gives distance, relative elevation	0.1 E	3 E	3 E	0	0	1	No difficulties foreseen w/lunar environment	Conceptual	Patterned target of minuscule lights, 12 total arranged in 3 diamond-shaped patterns of 4, separated about 5 ft
68. Lunar Hand Camera Graflex	Photography landscape distance, elevation	Stereo or single. Two film rolls, 300 frames. Resolution: 1 ft/500 ft	Camera: 4.5 w/ batteries Film: 0.5/roll	Camera: 70 Film: 20/roll	U	< 0.5	< 0.5/ photo	1	Designed for lunar environ. Level device must meet temp vacuum.	Prototype developed. Mil scale, level device needed. LT 6 mos E	Optical or pendulum level device, mil scale needed. Also, copy lens (special lens) for closeup photography of microstructure,etc.
69. Electronic Flash Braun F-25	Illumination for photography	Guide No.: 40 for ASA 25. Flashes/battery charge: 60. NiCd battery	0.8	20	0	0	0	1	Terrestrial design. Test in lunar environ. needed	Commercial item. Test and mod. lead time 6 mos E	Time included in camera operating time. May need larger battery to increase number flashes
70. Descent Camera Itek Corp.	Nested descent photog., LEM position	70 mm day/night; 2.25 x 2.25 format; 0 to 3 in./sec IMC; 58.6° view angle; f/3.5 Kaligar 52 mm focal length lens	6	230	75	0	0	1	Oper temp range: -65 to +165°F. Aircraft shock and vibration	Commercial item. Lead time to adapt 6 mos to 1 yr E	Contains 25 ft film plus 25 ft saturated web for in-flight processing. Should be inside LEM so film can be printed
71. Film Printer for Descent Camera	Print descent photography	Enlarges descent camera negative to 10 x 10 in. print	3 E	320 E	5 E	5 E	2/print E	1	Inside LEM	Undeveloped. Lead time 6 mos E	Times are pre-egress. Negatives from descent camera, processed in-flight, are used to print photographic "maps" of landing site area
72. Transponder	Distance to LEM landing site	Coded signal output, omni-directional, when interrogated	2 E	35 E	1 oper. 0.1 standby	0	0	1	Design for lunar environment	Conceptual instrument. Lead time 6 mos to 1 yr E	Part of scientific instrument package to be left behind. Used by post-Apollo missions for navigation relative to first landing site

TABLE V-1 (CONTD)

SELECTED INSTRUMENTS AND EQUIPMENT FOR APOLLO SCIENTIFIC MISSION

INSTRUMENT NAME MFR AND/OR INFORMATION SOURCE	MEASURAND OR USE	PERFORMANCE AND OPERATING CHARACTERISTICS	WEIGHT (LBS)	VOLUME (IN^3) DIMENSIONS (IN.)	POWER (WATTS)	SET-UP TIME (MINUTES)	OPERATING TIME (MINUTES)	HAZARDS	ENVIRONMENTAL CHARACTERISTICS	STATE OF DEVELOPMENT	COMMENTS AND SUPPLEMENTARY DATA
73. Calipers, Ruler, Spring Scale	Dimensions wt of soil density sample	Determine bulk density by measurement of cavity dimensions and weight of soil removed; assumes hole with regular geometric shape	2 E	20 E	0	1 - 5 E	5 - 10 E	1	Items must be tested for hard vacuum operation	Commercial items, adapted for lunar use. Lead time 6 mos E	Accessory items to flexible tool; assumes power-drilled sample hole
74. Proving Ring Penetrometer Attachment (w/o staff)	Penetration resistance	Simple stress ring w/dial indicator to indicate distortion; dial readout in force units. Range: 0-40 lb, limited by operator's lunar weight	0.5	10	0	0	< 0.5/meas.	1	Dial indicator bearings must be sealed for vacuum operation	Commercial item. Lead time to adapt, 6 mos E	Attachment for "Jacob's" staff (Item 4). Tip attachments for staff also desirable to vary stress on soil
75. Tethered Sphere	Bearing capacity	Assumes bearing capacity to support tossed sphere adequate for man. Probable critical factors are mass/X-sectional area ratio, drop height	2 E	85 E	0	0	~0.5/meas.	1	No difficulty foreseen w/lunar environment	Undeveloped. Lead time to develop, test concept 6 mos E	Conceptual device to enable testing of ground several feet ahead of astronaut, beyond reach of staff
76. Surveyor Soil Mechanics Test Apparatus (Thorman, 1963)	Shear strength, bearing capacity	Electric motor driven penetration plates (2), shear unit (1). Force, displacement monitored, analog voltage outputs	23 E	900 E	250 w-hr E	10 - 30 E	5 - 10 E	1	Designed for lunar environment. Vacuum welding may be severe problem	Surveyor prototype. Lead time to modify 6 - 18 mos E	Surveyor device modified with frame and soil anchors for reaction. Designed for "Bekker" trafficability method. Data has gen appl
77. Harvard Miniature Compaction Apparatus CN-4 35 Soiltest, Inc.	Density-compactive effort relationship	Spring-loaded compaction tampers, 20 and 40 lb	4 E	200 E	0	5 E	15 - 30	1	U	Commercial instrument. Lead time to modify, test 1 yr E	Lunar use would require only compaction mold, mold holder, compaction tamper, plus spring balance. Not conventional compaction test
78. Vane Shear Tester	Shear strength	0 - 200 lb torque	6 E	40 E	0	5 - 15	5 - 15	1	Vacuum welding may present problem	Undeveloped. Adaptation of commercial item. Lead time 1 yr E	Conceptual lunar design would limit depth to upper 2 ft, employ lightweight materials
79. Direct Shear Tester (Vey & Nelson, 1963)	Shear strength	Normal load applied by hanger weights; shear force through gear box, electric motor	6 E	300 E	U	15 - 30	5 - 15	1	U	Lab prototype. Lead time to develop 1 - 2 yr E	Prototype noted as possible pattern for lunar model. Suggest constant force springs for normal load
80. Spring Scale	Total sample weight	Simple weighing device with visual readout	1.7	3	0	0	1	1	Design for lunar environment	Common commercial item. Lead time to adapt 6 mos E	To check total weight of samples, etc., in return package for conformance to limit
81. Sampling Tool Package No. 1 (Chapter IV)	Sample acquisition	Contents: geol. hammer and chisel, shielding, magnet, sample scoop, planchet forceps, saw-knife, ultravacuum container.(6) samp. bags(26)	10.7	250	0	NA	70 E	1	Design for lunar environment	Undeveloped	Times are estimates without allowances for overlap with other measurements. Component items discussed in detail in Chapter IV
82. Sampling Tool Package No. 2 (Chapter IV)	"	Contents: as in 81 except 1 less ultravacuum tight container, 2 less sample bags. Add mechanical structure container and preserver (2)	12.8	323	0	NA	82 E	1	"	"	"
83. Sampling Tool Package No. 3 (Chapter IV)	"	Contents: as in 82 except 2 less sample bags. Add 3 ultravacuum containers, flexible power tool, erosion sampler, adsorber units (2)	51.1	1019	0	NA	227 E	1	"	"	"

Supplementary Discussion of Instruments and Equipment

For easy correlation, instruments and equipment are listed by the number assigned to each in the table. Items for which additional information is not available or information in the table is felt to be sufficiently complete are omitted in the following discussion.

No. 3. Petrographic Microscope

A breadboard model of a petrographic microscope has been designed and built for JPL by Armour Research Foundation for use on Surveyor (JPL, June 30, 1962, p. 48). In operation, it uses a sample consisting of particles in the 75-300μ size range, obtained by grinding a larger sample or by scooping loose surficial material. A monolayer of the particles is imbedded in heated thermoplastic tape. The objective lens is stepped through seven discrete 40-μ steps around the best image plane, insuring one good image for all particles. The images are picked up by a vidicon tube and the TV signal transmitted to earth. Optical magnification (x16) and resolution of the vidicon (25μ) allow the resolution of shapes of 5- to 10-μ particles. This instrument could be adapted for manned use but would give less information than a modified standard petrographic microscope to a trained operator. Preparation of a thin section sample needed for the latter, however, presents a considerable problem in the lunar environment and under mission conditions.

No. 4. Jacob's Staff

This is a conceptual tool, an adaptation of an aid sometimes used by field geologists. Additional design features which may be desirable include a mounting plate or head for the hand camera to stabilize it during photographic operations, particularly for surveying purposes, possible different tip configurations for use with the dial gauge penetrometer attachment, and a sighting aid to mount on the head. It should be of lightweight construction, probably tubular, but quite rigid.

No. 8. Erosion Particle Movement Sampler

This is discussed in more detail in Chapter IV-B.

No. 11. X-Ray Diffractometer

The X-ray diffractometer identifies compounds in a crystalline sample with a sensitivity of about 5 per cent of the total present. Identification means are the angles at which their crystal structures reflect the incident X-rays. A goniometer is used to scan the reflected X-rays in a single plane and determine the angle of reflection and the intensity at that angle. An electronic detector is used on these scanning devices to detect the X-rays.

The lunar diffractometer was developed for NASA by the Philips Defense and Space Laboratory for use on the Surveyor I spacecraft (Philips, no date). It uses a miniaturized 25-kv X-ray tube of special Philips design, achieving high radiation flux with good line focus. The copper X-rays are nickel-filtered to remove the k-beta line before they strike the sample holder filled with lunar material. The curved sample holder and the exit slit are rotated through a precise θ-2θ relationship and the X-rays are detected with a high-resolution, high-efficiency Amperex side-window proportional counter. The output of the proportional counter is preamplified, threshold detected, counted down by a scaler, amplified, then applied to the telemetering circuits. The resolution is very good for such a small radius instrument ($0.160° = 2\theta$ with a 6-mil slit), which is nearly as good as lab-type diffractometers.

The Surveyor diffractometer met or exceeded all of its technical design specifications (JPL, June 30, 1962). Results obtained from functional verification tests are:

Parameter	Specification	Test Result (avg of 19 runs)
Peak width at 1/2 height, deg (2θ)	0.22	0.205
Peak width at 1/10 height, deg (2θ)	0.43	0.357
Asymmetry (x/y)	1.12	1.09
Peak/background	27	29.4
Peak intensity, pps	2300	3290
Reproducibility of peak intensity, %	3	1

Other characteristics of the diffractometer were scan range of 7-90° scan speeds of 1/2 and 4 deg/min forward and 8 deg/min reverse, divergence slit 3° and receiving slit 6 mil. The instrument is in the final testing stages.

One disadvantage of this design, which could be serious, is that the sample must be prepared and placed precisely in the sample holder. It is felt that sample preparation on the moon could be a real problem. A diffractometer that uses the lunar surface as the sample would be desirable, assuming that this surface is finely divided. A proposed modification incorporating this feature, discussed by Weber and Bucher (1963, p. 73), would rotate the X-ray tube through θ° and rotate the detector through $2\ \theta^{\circ}$. This arrangement can be worked out. It may take a slightly larger and heavier instrument, but it seems like a very desirable design modification for APOLLO use.

No. 12. Infrared Spectrometer

The infrared spectrometer described in Weber and Bucher (1963) is not designed for compositional analysis but rather to detect and analyze the radiation incident upon and scattered by the lunar surface. Modification would be required to handle samples for absorption, emission or reflectance analysis techniques.

Lyon and Burns (1963) have described possible approaches to the analysis of rocks and minerals by reflected infrared radiation. Hunt and Turner (1954) discuss the determination of mineral constituents in rocks by infrared absorption measurements. Barnes (1958) found that 75 mineral species exhibit luminescence in the infrared.

Application of infrared spectrophotometry to the study of rocks and minerals is in its infancy and will require much more study to become a practical field tool. However, initial results are quite promising, and the well known application in the analysis of gases makes this a technique to be kept in mind for lunar applications. Lyon (1962) has recommended that infrared spectrophotometry be used in manned lunar laboratories.

A breadboard infrared interferometer has been constructed at Manchester University in England for planetary infrared spectroscopy in the 2-13 micron range (JPL, Oct. 31, 1963).

It should not be difficult to combine some of the design characteristics being developed for planetary studies with the standard laboratory designs and produce a workable instrument for either lunar sample absorption or reflectance studies.

No. 13. Differential Thermal Analysis (DTA)

DTA is a technique to measure enthalpic effects attending chemical or physical changes that occur in a sample as the temperature is varied at a selected heating rate. A thermally inert reference material, such as Al_2O_3 and a sample are placed in two identical cups heated together with continuous recording of the temperature difference between the two materials. Sample temperature lags behind that of the inert reference material during endothermal processes and exceeds it when exothermal reactions occur. DTA curves consist of thermal bands or peaks characteristic of the physicochemical reactions of the substance. DTA curves are unique for many mineral substances, and this is a definitive means of identification.

Reviews of instrumentation and applications of this technique are given by Gordon (1960) and Campbell, et al., (1959).

No DTA equipment has been proposed for lunar use in any report or literature available. Several scientists have expressed opinions in private conversations that DTA probably could yield some useful information without referring to the equipment that may be required. Frank Wilhite of JPL, in a private conversation, considered the possibility of combining DTA with the gas chromatograph. This would be done by using a common furnace for the two and, when the DTA indicated a transition had occurred, a gas sample would be run through the chromatograph to see what gases were evolved, if any. This approach would aid the gas chromatograph in identifying minerals and compounds.

A DTA instrument probably could be built similar to a portable commercial instrument made by Eberbach Corporation. It weighs only 8 lb, occupies 1 cu ft, and requires 450 w if the power cannot be reduced greatly. This instrument has a very simple furnace heating program in that the furnace is preheated to its maximum, then placed over the crucible assembly to heat the sample. This should provide an adequately uniform heating rate for the sample. Operation in a vacuum may introduce severe heat transfer problems.

It is believed that DTA alone would be of limited use in identifying components of a complex mixture. Its best application would be in combination with a gas chromatograph to determine water in possible lunar hydrated rocks or minerals.

No. 14. X-Ray Spectrometer

Use of the X-ray spectrometer, or spectrograph, in the analysis of rocks and minerals has been described by Rose, et al., (1963). The Surveyor I instrument was built by the Philips Defense and Space Laboratory, a division of Philips Electric Instruments Co., Mount Vernon, New York, (Weber and Bucher, 1963, p. 76). It has 13 fixed channels that will determine the elements Na, Mg, Al, Si, S, K, Ti, V, Mn, Cr, Fe, Ni, and Cu. Sensitivity considerations require the use of direct electron beam excitation, even with its higher background, to achieve as high an X-ray intensity as possible with little power. Its sensitivity is about 0.1 per cent for most elements, 0.5 per cent for Ca and 1.0 per cent for Si. The instrument uses 11 GM counters and four proportional counters, one for a nondispersive channel which receives all X-rays and performs a pulse height analysis.

Estimates in the table are for a modified instrument to meet APOLLO requirements. Desirable modifications would be to use two or more nondispersive channels with scintillation detectors and good pulse height analyzers for a broad range of data and to use the lunar surface directly as the sample or perhaps just place lunar material in the proper place with no preparation.

Developmental problems with the Surveyor instrument (JPL, April 30, 1963a) included: (1) alignment difficulties with the collimator; (2) cross-talk between channels; (3) susceptibility of channel amplifiers to corona discharge damage from the electron gun; and (4) building up of a charge on irradiated nonconductors resulting in deflection of the electron beam. Development and studies of possible modifications are continuing.

No. 15. UV-Visible Absorption Spectrometer

The solar furnace used for vaporizing the sample in the Surveyor prototype built by Beckman reaches a temperature of 4000°C. A mirror reflects sunlight through the vaporized sample. The dual-beam ratio system measures the difference in transmission between reference beam and absorption beam.

This lunar surface analyzer is designed to operate only when the sun is less than 30° from the moon's vertical. It uses a sun tracker to hold the sun image on the focal point of the furnace and to align the solar furnace image on an appropriately prepared spot and illuminate the grating through separate beams. This insures identical optical transmission for accurate beam comparison.

No. 16. UV-Visible Spectrometer

Prototype models of a scanning UV-visible spectrometer covering the 200 to 600 millimicron range have been constructed by AVCO Corporation (Weber and Bucher, 1963). Few details were given in the cited reference, and no additional information could be obtained from AVCO or NASA. This is a scanning instrument to observe and analyze the radiation incident upon and scattered by the lunar surface. It has a grating monochromator with field of view unmodified by optics. The resolution is about 10 millimicrons in the 200 millimicron range. Photomultiplier tubes of the 1P21 or 1P28 type are used as a detector.

This ultraviolet-visible spectrometer could be used for measurements of reflectance from various strata or areas of the moon, and possibly some rock types could be identified if the experiments could be carried out under closely controlled conditions.

No. 17. Neutron Activation Analyzer

Trombka and Metzger (1963) describe several neutron activation analyzing systems for space use. The one described in the table is the best developed thus far. Descriptions of it also have been written by Weber and Bucher (1963) and C. S. Schrader et al., (1962). The neutron source is a miniature accelerator type developed by Sandia Corporation and is only 6 cm long and 3 cm in diameter. Lifetime is $> 10^7$ pulses. Pulsing is accomplished at the ion source. The d-c accelerating potential of -80 kev is obtained from a Cockcroft-Walton voltage multiplying circuit. The generator requires about 100 w of power while operating. A copper shield protects the detector from direct neutrons and X-rays produced in the neutron package.

The gamma ray detector is a scintillation type using a 2-in. long by 2-in. diameter NaI (Tl) crystal on an Ascap ruggedized photomultiplier tube.

The order of procedure with this system on the moon would be: (1) determination of the natural and cosmic-ray induced radioactivity of the moon's surface using just the detector and pulse height analyzer before the neutron generator is turned on; (2) primary analysis of the surface composition through detection of the gamma rays produced by the inelastically scattered neutrons from the neutron generator; and (3) pulse height analysis of the activation and capture gamma rays to enhance and substantiate the primary results. A typical gamma ray pulse height spectrum is shown by Schrader et al., (1962).

Another system similar to the above was designed and built by the same group of labs (Schrader et al., 1962). An important addition was thermal control of the detector to ± 1°C. A 128-channel pulse height analyzer was used.

Other neutron activation analysis systems have been proposed by Fite et al., (1963) and Monaghan et al., (1963). It has been pointed out by J. Trombka (1962) that it will be necessary to use a neutron generator that will yield 10^9 neutrons/sec at the target and a PHA with at least 256 channels to obtain useful data on the composition of the lunar surface. No miniaturized or space-hardened equipment with these capabilities has been built although work is in progress now to develop such a system with reasonable power, weight and volume requirements (Trombka, 1963).

No. 18. Alpha Scattering Spectrometer

Compositional analysis by alpha particle scattering is a new technique proposed for lunar application by Prof. A. Turkevich of the Fermi Institute of Nuclear Studies of the University of Chicago.

Alpha particles from a radioactive source are caused to bombard a sample. Some of the particles are scattered back from nuclei within the sample and strike a small semiconductor detector placed at a high scattering angle. The amplified pulses from the detector are proportional to the energies of the scattered alpha particles. Pulse height analysis of the detector output provides a digital energy spectrum of the scattered alphas from which the mass numbers and abundances of the nuclei in the sample may be obtained. Additional valuable information is obtained by simultaneous measurement of the proton spectrum as emitted by certain of the lighter elements when bombarded by alpha particles. Automatic cross-correlation of the alpha and proton data may be done by computer (JPL, April 30, 1963b, p. 122-126; Weber and Bucher, 1963, p. 78).

Prototypes of the Surveyor lunar alpha scattering spectrometer have been built by the University of Chicago Laboratory of Applied Science and have been evaluated by JPL. The alpha sources, curium 242 providing 6 Mev alpha particles, were prepared by Dr. J. H. Patterson of the Argonne National Laboratory. Resolution and accuracy are sufficient to distinguish between major rock types such as acidic, intermediate, basic and meteoritic.

Modifications of the Surveyor instrument for manned missions should be relatively simple, and marked improvements can be expected over the next few years in the relatively new field of semiconductor nuclear particle detectors for spectral applications. Recent reviews of the latest developments in detectors and their applications are given by Glos (1964), Goulding (1964) and Nucleonics (1964).

No. 19. Neutron Scattering

This technique, closely related to neutron activation analysis, sometimes is called the neutron-neutron method. It involves bombarding rocks with fast neutrons and then measuring the scattered ones after they have been slowed down by the formation. The instrument detector responds only to slow neutrons, the relative number of which is proportional to the concentration of hydrogen nuclei present. The slowing process involves a reduction in energy from the Mev range to thermal energies (50 ev).

Advantages of this method include independence of density of bombarded material, insensitivity to natural radioactivity background and independence of neutron capture effects producing gamma rays. The main disadvantage is its reponse to elements of high neutron capture cross-sections such as S, Cl and B. The data in Table V-1 are based upon a neutron-neutron portable instrument described by Johnson (1962). The depth moisture probe has a 5-mC fast neutron source of radium 226-beryllium within a probe 15 in. in length and 1-1/2 in. in diameter. It weighs 45 lb complete with a lead and paraffin shield 6 in. in diameter and 8 in. long. The electronics consists of a portable battery-powered scaler with five glow-tube decade counters, a spring-wound timer and weighs about 35 lb.

No instruments of this type have been designed for lunar or space use. For the APOLLO mission, one of these probes using a Po-Be or Pu-Be source could be modified to a reasonable weight and volume. The electronics from any other radioactivity experiment could be used with this system, or something very simple could be worked out just for this experiment. All that is needed is a scaler-counter to measure the total counts and put the information in useful form for recording or telemetry.

No. 20. Gas Chromatograph

The Beckman Lunar Gas Chromatograph was designed for the Surveyor I spacecraft (Donner, 1962 and 1963) and in its present form could not be used for APOLLO. A modification could be more or less complex than the Surveyor type, depending on the measurements it is designed to make. The Surveyor I chromatograph uses a pyrolysis oven heated to 150°, 325° or 500°C and three parallel columns with three detectors. The instrument can separate and identify 28 constituents that may be on the lunar surface, including fixed gases, water, ammonia, aromatics, saturated or unsaturated hydrocarbons, acids, alcohols, esters, ethers, aldehydes, and ketones. The 28 constituents were picked in consultation with JPL and other scientists as the most likely to be on the moon or the ones that need to be identified to determine if there is now or ever was life on the moon.

The constituents to be measured could be changed to include any of hundreds of compounds boiling at 250°C or less. The three columns are an absorption column filled with molecular sieves, a packed partition column and a capillary partition column. The detector is a new, very sensitive type capable of detecting 10^{-10} moles. It uses a voltage breakdown principle similar to a neon bulb and is ac-coupled to the amplifier to eliminate zero drift.

The chromatograph will operate automatically after it is started; one complete analysis requires 100 min. It contains enough carrier gas for 50-hr operation. It can be built into the landing capsule and samples brought to it, or it may be moved to the lunar surface where a simple pushbutton operation can be made. The chromatograph has been fully tested at JPL for takeoff shock requirements and for extreme heating environments on the moon (White, 1963; Wilhite, 1963; and Wilhite and Burnell, 1963).

No. 21. Mass Spectrometer

Several mass spectrometers have been designed for space use, each for a specific mission. This one (Schrader, 1962; Smith, 1963) is the double-focusing magnetic type that detects ions by means of collectors for masses 1, 4, 14, 16, 18, 28, 32, and total current. It was built for the Goddard Space Flight Center by Consolidated Systems Corporation for use on satellite S-6 in earth orbit at 250-600 km. The present instrument weighs 23 lb but can be reduced to 12 lb. It was designed to identify and measure the free radicals and thermally energetic particles encountered by the satellite at 200 to 1000 km from the earth. It will operate over a range of 10^{-4} to 10^{-10} torr.

It is felt that this instrument does not have the sensitivity and is not suitable in its design to obtain useful data on the moon without considerable modification.

Another mass spectrometer for space use was developed for the Mariner C by Consolidated Systems Corporation for the investigation of the Martian atmosphere (Smith, 1963). This instrument will be required to scan the mass spectrum from mass 12 to mass 50 while falling through the Martian atmosphere. The required resolution is unity separation at mass 25 and the dynamic range is three decades.

The design restrictions for the Martian mass spectrometer were 6 w of power, 5 lb in weight, channel capacity of 500 bits/spectrum, and magnetic leakage field of 1 γ at 3 ft. The basis for this system is the quadrupole mass filter which possesses special advantages because of its light weight and nonmagnetic operation. This program required advanced research and development in optimization of the quadrupole design parameters and study of optimum detector, mass scanning and data handling systems. This mass spectrometer would be operating in an atmosphere which would be much greater than that which exists on the moon.

Other space mass spectrometers have been built by Consolidated and flown on rocket probes. One such unit, using the quadrupole mass filter analyzing system, weighed 29 lb, required 40 w power and scanned all masses below 45 amu in 2 sec with unit resolution to 30.

No. 22. Mass Spectrometer

Recent studies conducted at Bell and Howell Research Center by Dr. Wilson Brubaker indicate that the quadrupole mass filter analyzing system offers the most promise for a good, lightweight, nonmagnetic space mass spectrometer. This system has been used in several of their rocket probe mass spectrometers and can be varied to suit the particular design parameters. The mass scan can be varied easily from mass 2 to mass 50 just by varying the d-c voltage. Higher masses may be analyzed by varying the RF voltage. Scanning rates can be as fast as 2 sec if the source pressure is 10^{-8} torr or higher. Scanning rates at lower pressures are slower because of fewer atoms available, requiring at least 4 hr to scan mass 1-100 at 10^{-14} torr. This restriction would hold for any type since there is such a scarcity of atoms to ionize in this pressure range. A pumping system of some sort would be needed for sampling if atmospheric analysis on the moon is attempted. Dr. Brubaker has conducted a study for the George C. Marshall Space Flight Center directed toward selection of apparatus for analysis of the lunar crust and atmosphere (Brubaker, 1963). He proposed to use a heated filament to vaporize the moon sample into the mass spectrometer and to use a quadrupole mass filter analyzing system.

The time of flight principle is very promising for a good lightweight space instrument since it does not require high magnetic fields for focusing. It does have serious limitations in its readout system if 10,000 spectra/sec are to be recorded and telemetered back to earth. One possible time of flight design was suggested by Schrader (1962) of the Space Physics Laboratory, Air Force Systems Command, Inglewood, Calif. He proposes to analyze the particles only one at a time using a 100-mc oscillator as the timer and the electron multiplier as a high-sensitivity detector. Since each count is recorded individually, the total intensity of any mass peak can be obtained precisely by summation of the counts on the ground. The output is digital, requiring no ADC equipment. With this design, even a 10-cm flight tube gives a resolution of 1 amu in 60. The mass range is continuous for masses 1 through 50 and can be extended higher if desired. Naturally occurring ions could be analyzed by turning off the ion source. Further development is necessary in several areas: (1) single-particle counting; (2) instrument outgassing; (3) oscillator circuits for precision timing; and (4) scaler circuits.

Weber and Bucher (1963, p. 80) proposed a mass spectrometer to determine composition of the lunar surface and atmosphere in the mass range 1-1000 or greater. They also proposed to measure the total pressure of the lunar atmosphere (10^{-13} to 10^{-14} torr). They would use a laser or electron beam to volatilize the lunar crust and analyze the volatilized material with either of the TOF, quadrupole or magnetic or other type analyzer. Their design restrictions would be 5-10 kg, less than 0.35 cu ft, power of 6 w, mass range 1-1000, resolution 1/100 ($\Delta M/M$), sensitivity 10^{-14} torr, and a precision of 1 per cent. The scanning time probably would be quite long with this high mass range and low pressure.

No. 23. Gamma Ray Spectrometer

This instrument is a necessary part of the neutron activation analysis system. Its main function apart from the activation analyzer is to measure the natural radioactivity of the lunar crust and to determine what radioisotopes are present. It is expected that the main radioisotopes will be K^{40}, U^{238}, Th^{232}, and decay products.

The spectrometer described in Table V-1 was built for Rangers III, IV and V. It was proposed and designed by scientists at Los Alamos Scientific Lab, University of California, La Jolla, and JPL (Metzger et al., 1962; JPL, Oct. 1, 1962). It consists of three units: a detector; high voltage supply; and pulse height analyzer. The detector is a 2-3/4-in. by 2-3/4-in. CsI ($T\ell$) scintillation crystal surrounded by a 1/8-in. thick plastic scintillator and all mounted on a 3-in. photomultiplier tube. The plastic scintillator was added to eliminate counts due to charged particles which will produce a pulse in the plastic while the gamma rays will not.

The pulse height analyzer was made by Radiation Instrument Development Laboratory and has 32 channels with storage of 2^{16} counts in each channel. One channel accumulates all pulses with amplitudes exceeding that of channel 31. Any of several pulse height analyzers designed and built for Surveyor (64, 96 and 128 channels) also would be adequate for the spectrometer in measuring the K^{40}, U^{238} and Th^{232} present.

The high voltage supply was designed at JPL to achieve the best regulation in a small package over the 1500-1800 v range required for operation of the detector phototubes. The supply is a d-c to d-c inverter system that uses the 31.5-v primary supply of the spacecraft. Zener-bridge control circuit regulation yields a regulation of 0.05 per cent at constant temperature.

No. 24. Alpha Ray Spectrometer

This instrument would detect natural alpha ray activity and would be part of the alpha scattering spectrometer (No. 18) as indicated in Table V-1.

No. 25. Gamma Ray Backscattering

An instrument designed for astronaut use could be simpler but probably not smaller or lighter. The Surveyor prototype did not meet all JPL functional requirements. The accuracy on unconsolidated materials was poor, but these results are at least partially ascribed to the method used for measuring bulk density of the test materials.

The Surveyor instrument uses a 40 mc iridium-192 gamma source collimated by heavy shielding. Measurement of average density to a depth of about 10 cm is accomplished. One commercial field instrument consists of a 20-lb probe with a 3-mc Cs^{137} source and a 33-lb portable scaler containing a wet-cell, rechargeable power supply.

No. 26. Kreisman Vacuum Gauge

The Kreisman gauge is one of two commercially available types considered capable of measuring lunar atmospheric pressure. The other is described by Young and Hession (1963) and uses a small pulsed filament as a trigger. The filament is not used during the period of operation. The commercial trigger gauge tube and control are marketed by General Electric Co. as Models 22 GT210 and 22 GC201, respectively. No space model of the filament-triggered gauge has been developed.

Possibly, the most advantageous use of the atmospheric pressure measurement would be to monitor the loss of rocket exhaust contamination and eventually record the true lunar atmospheric pressure some time after the LEM has returned to earth.

Another method proposed (Weber and Bucher, 1963) for measuring lunar atmospheric pressure is to sum the partial pressures of all constituents detected by a mass spectrometer.

No. 27, 28. Sample Culture With pH Readout or Radioisotope Readout

The basis of this measurement is the experimental detection of the revitalization of any possible dormant simple microscopic life forms when they are placed in a nutrient environment similar to that found on earth. It is assumed that visual photographic or vidicon methods will disclose any microscopic life forms.

Samples of the lunar surface would be placed on some suitable medium in an environment calculated to promote rapid growth. The effects of this growth could be detected in a number of ways including microscopic observation; radioisotopic measurements of evolved carbon dioxide; pH changes in the nutrient; turbidity changes; etc.

The growth period could be coincident with the astronaut's return to earth and would provide a first estimate of the hazard possibilities on landing. Further testing could be done during a quarantine period if this were found to be desirable. This would require location of the instrument in the command module.

Culture techniques are standard in medicine and biochemistry so that much information is available on present methods in this field. The problems are so diverse and varied that they preclude adequate coverage in this study; efforts have been concentrated on space instruments.

Most investigations to date have dealt with the unmanned detection of life on Mars (Chemical & Engineering News, 1964) or upper atmosphere investigations on earth (Soffen and Stuart, 1963).

Sample collection devices range from the sticky string of the Gulliver experiment (Levin and Carriker, 1962) to vacuum probes and aspirators with cyclone separators (Tuttle, 1963). In any APOLLO measurements, the samples will be collected by hand methods and transferred to the nutrient chamber.

Culture media which could be used include solids such as nutrient agar, trypticase soy agar, or rose bengal agar, and broths such as trypticase soy broth, Sabouraud, or fluid thioglycollate (Soffen and Stuart, 1963). It would be necessary to perform parallel control experiments with no added sample to prove that no contamination was present from sources other than the samples.

The most advanced growth detection technique is the radioisotopes biological probe used in the Gulliver experiments. It is based on the detection of radioactive metabolic end products from organisms grown in a C^{14} tagged medium (Levin and Carriker, 1962). Other radiotracers being investigated include S^{35} and H^3 in many different compounds. This instrument in its present form weighs about 1.5 lb and requires 250 mw for the detection system.

Other growth detection schemes include microscopic examination, pH and turbidity changes (Wolftrap experiment) and fluorimetric observations (Multivator experiment).

Proposed chemical methods of detection of life forms are based on the instrumental detection and measurement of organic compounds which are characteristic components or products of living matter. Chemical life-detecting techniques being investigated for exobiology studies include (Chemical & Engineering News, 1964):

a. Optical rotary dispersion profiles (Dr. Ira Blei; Melpar, Fairfax, Va.) to detect adenine

b. Mass spectrometer (Dr. Klaus Biemann, Massachusetts Institute of Technology) to detect peptides and amino acids by pyrolosis products

c. Ultraviolet spectrophotometer (Melpar) to detect peptides

d. Gas chromatograph (Dr. W. Wilhite, JPL; Ames Research Center Scientists) to detect any biologically significant gases

e. J-band life detector (Drs. E. Walwick and R. Kay, Philco Research Lab) to measure spectral changes due to aggregation of dibenzothiocarbocyanine dye when it is absorbed on protein micromolecules

Consideration was given to the value of b, c and d for this measurement in the computer evaluation analysis of optimum instrument combinations described in Part II, Chapter VI.

No. 29. Solar Plasma Spectrometer

This instrument is to make measurements of (1) the low-energy charged-particle (electrons, protons and heavier positive ions) environment of the lunar surface--both the quiescent plasma (extension of sun's atmosphere) and the solar wind (corpuscular streams, not in thermal equilibrium) and (2) the time variations (including day-night) in the lunar plasma environment.

The Neugebauer electrostatic velocity selector consists of concentric quarter-circle cylindrical plates with variable-applied electric potential difference. It measures the speed as a function of the potential difference and the charge/mass ratio of the velocity-selected particles. The Rossi probe is a Faraday-cup type measuring energy and charge of the incoming particles by the retarding electric potential method. The Neugebauer instrument is a JPL development and the Rossi probe was designed by Professor Rossi and associates at Massachusetts Institute of Technology.

The energy range is a few electron volts to about 6 kev, the minimum flux to be detected about 10^3 particles/cm^2-sec. Angular resolution will be crude--about a 20-deg acceptance angle. Preferred directions are along moon-sun line (both directions) and radially in the plane of the ecliptic (the normal to the ecliptic plane is the direction of the solar magnetic dipole lines).

The magnetic field must be measured simultaneously with the particle flux. Total gas pressure should be measured simultaneously, especially over the lunar diurnal cycle, to measure possible gas accumulation on the dark side of the moon caused by solar wind driving.

Desirable modifications include (1) use of solid-state charged particle detectors and pulse counting instead of vibrating-reed type electrometer and (2) more sophisticated angular and time dependence measurements of the flux-energy spectrum.

No. 30. Survey Rate Meter

The ionization chamber of the survey rate meter is a 0.010-in. thick, stainless steel sphere, 5-in. in diameter, containing one liter of argon at 4 atmospheres pressure. Area density of the spherical shell is 0.2 gm/cm^2. One count/500 sec is the equivalent of 1.2 mr/hr.

There are two of these instruments in the recommended instrument-equipment packages. One is mounted on the LEM and has a visual rate output meter. Its use is to measure possible belts of magnetically trapped radiation during the apprach to the moon and to determine the ionizing dose rate after landing and before astronaut egress. The other instrument will be in the unattended scientific instrument package and will measure ionizing radiation flux over one or more lunar diurnal periods.

No. 31. Particle Spectrometer

Of the several particle spectrometers which have been used in space probes, four are listed in Appendix D as items 4 through 7 of sheet 1 under the meteoroid and radiological measurements study group. None of them meet ideal requirements; the one listed in Table V-1 most closely approaches these at a reasonable payload cost. The instruments fall short of ideal requirements in their upper energy limit (1000 Mev desired but heavy shielding required) and in flux capability (up to 10^9 particle/cm^2/sec per steradian desired).

No. 33. Chemical Reactivity Detectors

Temperature rise is used as a criterion for chemical reactivity with lunar surface materials. An alternative technique would be use of temperature-sensitive paint on the samples. Samples of inert material also should be lowered to the surface with any temperature-sensing technique for comparison purposes.

No. 34. Personal Dosimeter

This is a quartz fiber electrometer shaped like a fountain pen. A similar instrument is manufactured by Beckman Instruments, Fullerton, Calif. Optics modification is required for astronaut use while wearing a pressure suit.

No. 35. Meteoroid and Lunar Ejecta Detector

This meteoroid and lunar ejecta detector is actually a combination of two instruments in a conceptual design by A. D. Little, Inc.: (1) a sensor which distinguishes between meteoroids and lunar ejecta and determines the trajectory and velocity of the latter; and (2) a momentum sensor to determine the magnitude and direction of the momentum vector for the lunar ejecta.

The first instrument relies on the following principle. The path of the particle is determined by locating two points on the trajectory where the particle passes through sensing screens; the velocity of the particle is determined by measuring the time-of-flight between these two points.

The sensing screen consists of a thin insulating film separating thin conducting strips; thus, the insulating film serves as a dielectric in a condenser in which the metal strips are electrodes. (A hemispherical surface is illustrated.) The plastic is such that, at the site of penetration, the heated products will become conducting when penetrated by a low-velocity fragment of lunar debris.* The metallic surface on one side of the film consists of 16

*Some care may be required in selecting the plastic film. If mylar proves non-conducting when penetrated by a low-velocity fragment, it may be necessary to use a chemically reactive and exothermic material. such as cellulose nitrate. Because the impact velocity is low, the necessary tests may be conducted without major problems in a laboratory.

strips or sectors; the metal on the other side of the film also consists of 16 strips or sectors arranged to be orthogonal to the metal pattern on the reverse surface.

The passage of a particle through the surface thus will be sensed as a discharge of a condenser formed by the two penetrated metal sectors; hence, the sensing surface is divided into 256 sectors for identification of the site of penetration (see Figure V-1).

Two such concentric sensing surfaces are used to detect the passage of a particle of lunar debris. The penetrated sector of each sensing surface is established, which will establish the trajectory, and measurement of the time interval between penetrations will permit determination of the velocity. Lunar ejecta can be sensed by this equipment and will be distinguishable from meteoroids, since meteoroidal impact will result in only one hole. Vaporization of the debris from a meteoroid impact will spread the momentum over so large an area that the second surface will not be penetrated. The spreading of vaporized debris is discussed in detail in a report on meteoroid bumper design (Johnston et al., 1963).

The following is a circuit design that would be economical on circuit elements, though it is probably not minimal in its power requirement and certainly not minimal in the number of bits required to convey the information. As shown in Figure V-2, a penetration which causes a discharge between the two metal strips will result in signals A and B (of opposite polarity).

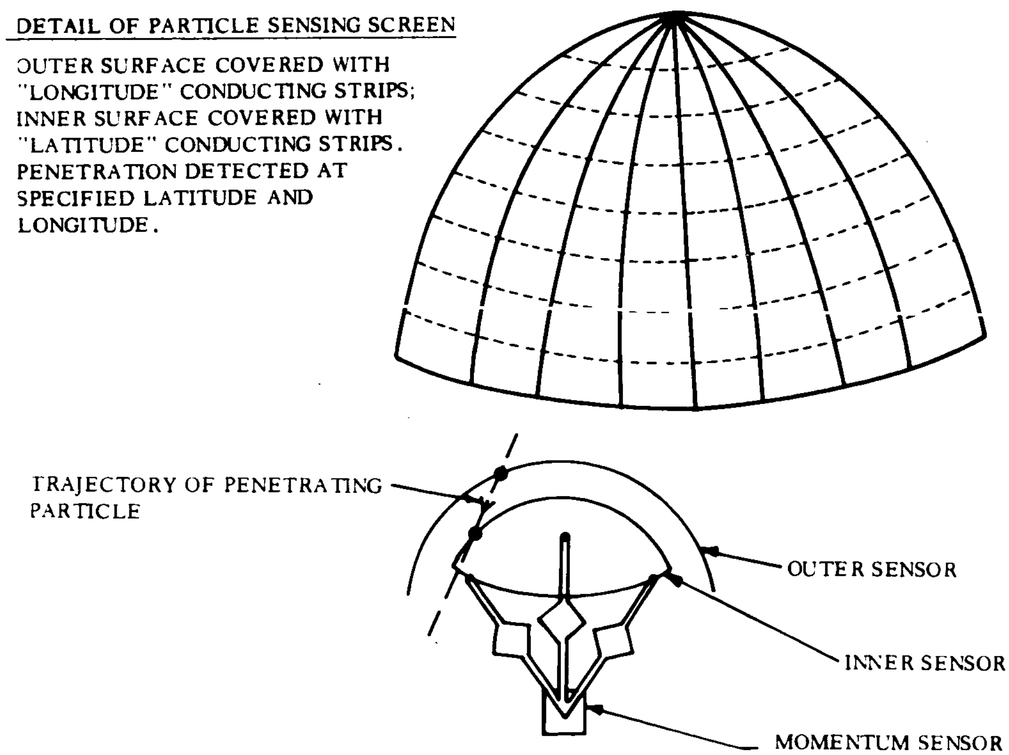

Figure V-1. Particle Trajectory and Momentum-Sensing Device.

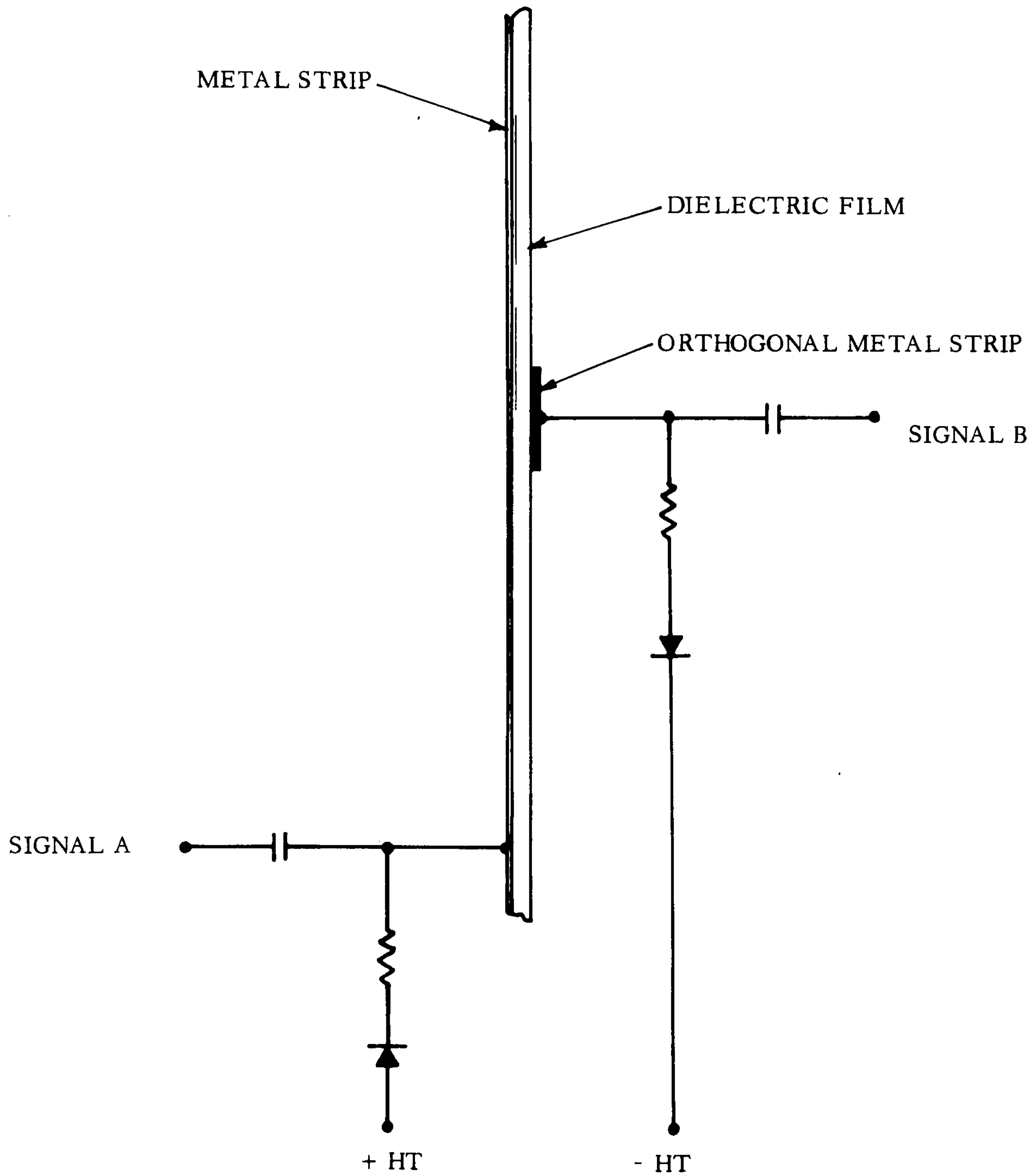

Figure V-2. Circuitry Concept for Particle-Sensing Screen.

A similar pair of signals, C and D, will be derived from the second sensing surface. Attention is confined to a single set of 16 metal strips which correspond say, to signal A. It is then desired to designate which of the 16 strips has been penetrated.

These strips are numbered from zero to 15 and signal A from strip "n" is used to set a 4-stage binary counter to "n". After a brief delay, an oscillator is turned "on"; this oscillator drives the counter. The oscillator is shut off when the counter resets. The number of the penetrated strip is recorded as the number of oscillator pulses required to reset the counter to zero (i.e., complement of "n").

A 4-stage counter is required for each set of signals, A, B, C, and D. By arranging slightly different delays between the setting of the counter and the turning on of the oscillator, one can provide that the pulse trains for signals A, B, C, and D occur successively. This permits sequential use of a single channel of transmission to the lunar data handling and relay point.

The power supply required for this system includes a high voltage supply with adequate potential to produce breakdown when the dielectric film is penetrated.

The momentum sensor uses a microphone sensor or a fast-damped, microinch displacement, solid-state sensor* as a means of determining the impulse transferred. (The microdisplacement sensor appears to offer the prospect of achieving a more omnidirectional response than the microphone.)

An absorbing surface would be placed beneath two thin foils used to exclude meteoroidal impacts. These two thin outer foils would be penetrated by the low-velocity lunar ejecta which would be stopped in the absorbing surface. The outer foil would, however, serve to sublime a meteroroidal particle, and the momentum of its vaporized debris would be absorbed by the second foil.

The absorbing surface would be mounted on a restorative system in such a manner that its displacement could be sensed along three orthogonal axes by means of microinch displacement sensors. The measured displacements, together with a knowledge of the impact point, the inertial characteristics of the absorbing surface and the restorative constants of the support would permit one to resolve the momentum into vector components. Tentatively, the absorbing surface is visualized as consisting of aluminum "hexcel" expanded metal; the objective of the expanded metal would be to lessen the risk of splash from the surface on impact.

In addition, an "anticoincidence" instrumented surface could surround the absorbing surface described above. Its purpose would be to

*Proprietary item at Arthur D. Little, Inc.

sense and reject any impacts in which the impacting particle was not stopped in the absorbing surface. A conceptual sketch of the momentum-resolving instrument is found in Figure V-3.

Such an instrument could supplement the trajectory data of the ejecta by eliminating meteoroids and using momentum vectors. While this provides the momentum, the velocity would have to be determined by a time-of-flight process for the penetration of the two thin surfaces used to reject meteoroids. The only disadvantage of this is the limitation on sensitivity; if the area is made large to intercept a low flux, the mass of the momentum-trapping cavity increases, making it less responsive to light fragments.

A system fully instrumented to measure trajectory, velocity by time-of-flight and momentum vector would be redundant. The redundancy could be preserved as a check on the trajectory, or the momentum measurement could be confined to a single (vertical) component.

No. 36. Meteoroid and Lunar Ejecta Detector

This is a somewhat similar instrument to the A. D. Little concept described by Weber and Bucher (1963). It also uses two capacitor sheets. They consist of thin films, about 5000 Å thick, composed of aluminum oxide as dielectric and evaporated aluminum films on both sides as conductors separated by a distance of about 10 cm. The second or back sheet is bonded to a 0.0305-cm thick stainless steel plate which acts as an acoustic detector. The capacitor sheets are divided in sectors also so that velocity (speed and direction) is obtained and the acoustic detector signal gives the momentum of the particle. Time-of-flight between capacitor sheets is measured with a front-plate-pulse-gated electronic clock. Two sensor arrays of about 500 cm^2 each, with the sensitive areas forming an X-configuration are designed for Surveyor. (Each area is situated at about 60° to the lunar vertical.)

Capacitor sheets have been tested at liquid nitrogen and 130°C temperature without damage. The acoustical sensor has been developed and qualified at Ranger Prototype Test Model (PTM) test. Other components (including electronics) were ready for breadboarding in November 1962.

No. 37. Susceptibility Bridge

The instrument described is part of the Surveyor surface geophysical instrumentation developed in prototype for JPL by Texaco Experiment, Inc. A subsurface instrument, for borehole use, based on the same principles, has been designed and tested, but the optimum configuration has not been realized (Bollin, 1962).

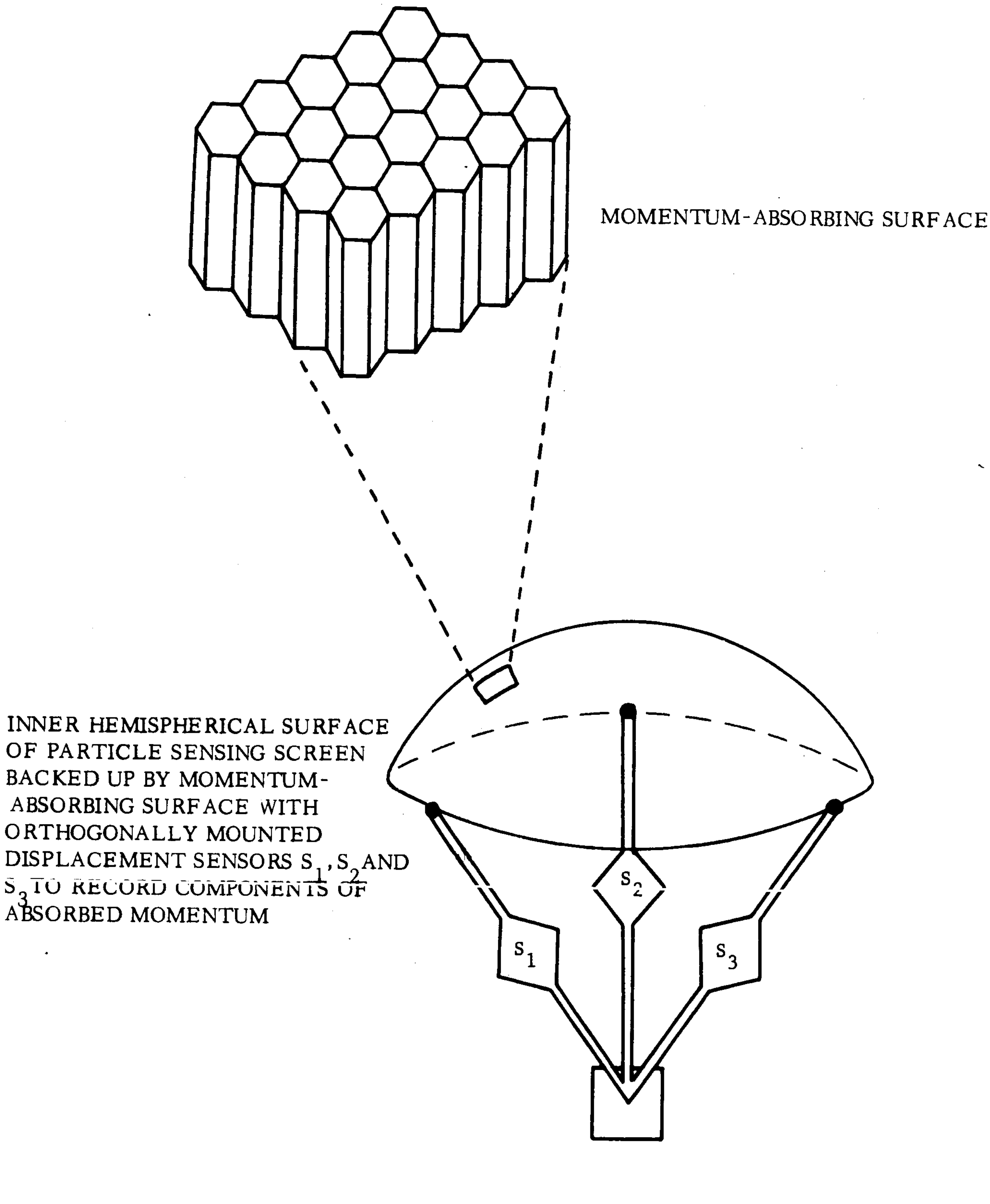

Figure V-3. Momentum-Sensing System.

A possible modification of the surface instrument to aid in measuring anisotropy in magnetic susceptibility at a point would be to use elliptical coils, with the major response in the direction of the major axis of the coils. This concept needs theoretical and experimental verification, however.

No. 38, 39. Fluxgate and Low-Field Helium Magnetometers

The low-field helium magnetometer was chosen for the computer evaluation analysis because it has less difficulty with the long-term zero drift and thus would provide more accurate absolute measurement of the magnetic field. Information available on the Mariner II fluxgate instrument was very limited.

A portable magnetometer for magnetic surveys is considered desirable on the second APOLLO flight. Either of these instruments could be adapted for portable use, though in present form they are more suitable for operation in a geophysical observatory. A design study of the portable instrument should determine which type is the more suitable.

No. 40. Electrodes, Voltmeter, Cables, Current Source

These items are components of self-potential and resistivity measuring equipment available commercially. The descriptions are for conceptual modifications of the items for lunar use. Examples of commercial equipment are Geophysical Instrument and Supply Company Models VP-G and SP-5R. Extensive investigation of contact resistance problems under lunar vacuum conditions is needed to determine the feasibility of these measurements.

No. 41. Charged Dust Detector

The instrument described is a conceptual modification of the Neugebauer solar plasma spectrometer to detect any finely divided, electrostatically charged particles (lunar dust) which may be present in suspension above the lunar surface. A possible charge mechanism is simultaneous photoelectric emission by unconsolidated particles and the lunar surface, resulting in suspension of the unbound particles by electrostatic repulsion (Weber and Bucher, 1963).

The charge/mass ratio would be much smaller for the dust particles than for the solar plasma constituent particles. Since mass and charge of the particles are not both known or easily measurable, speed and charge/mass ratio cannot be separated. Measurement would be qualitative, yielding fluxes of charged particles in groups specified by product of speed and charge/mass ratio.

An array of six instruments arranged in three orthogonal directions, one aligned with the lunar vertical, would be desirable to investigate possible directional effects.

No. 43. Quartz Gravity Meter

The instrument described is a proposed modification of a commercial instrument. Design for a dynamic range and gravity magnitude appropriate to the lunar environment is needed, and an electronic null with dial readout is proposed to replace the optical null arrangement which would be difficult for the astronaut to use while in a pressure suit.

Feasibility of this instrument was established by Texas Instruments Incorporated in a lunar gravity study under Contract No. NASw-581 for NASA, Washington, D. C.

No. 45. Lunar Seismometer

The ITT-Lamont instrument described is a combination 3-axis long-period and single-axis (vertical) short-period seismometer. The output of the vertical feedback loop in the long-period seismometer, used to maintain the seismic mass near the center of its linear range, yields tidal gravity information when accompanied by a measurement of the temperature of the instrument. The latter is necessary to remove temperature effects on the output data.

This prototype instrument was developed as part of the Surveyor payload. At the time of the final technical report (Lamont Geological Observatory, 1962), development was considered incomplete and a number of modifications and areas for design study were suggested.

Modification for APOLLO missions would include removal of the automatic coarse leveling system, as this would be accomplished by the astronaut. Estimates given in Table V-1 include weight reduction measures suggested in the final report. The combination instrument would perform the functions of instruments 42, 47 and 48. Under present estimates, it would require less weight, volume and power than the combination of those three. For these reasons and because it ranked higher in the computer evaluation analysis than any of the single-purpose instruments, it was included in the proposed unattended scientific instrument package.

No. 49. Portable Refraction Seismic System

Information available on this system is very limited. Additional study, both theoretical and experimental, of active seismic techniques suitable for use on APOLLO missions appears needed.

The system described envisions use of explosive charges on the surface as acoustic energy sources. No drilling for charge placement is projected. Indications of field calibration studies are that a maximum charge size of less than 1 lb is needed for a 2000-ft line array. Because of hazards with explosive sources, various nonexplosive mechanical energy sources are also under consideration, as well as explosive sources with the energy confined or directed so as to be harmless.

No. 50 - 55. Temperature Measurement Devices

These six instruments can be divided into two classes, thermocouples and resistance thermometers. A third class of potential application is that of thermistors, which are semiconductive resistance thermometer elements, usually with a nonlinear response.

Thermocouples consist of junctions between dissimilar materials, usually metals. An emf is generated when two junctions are held at different temperatures. Accurate temperature measurements require that one of the junctions be held at a stable known reference temperature, usually an ice bath in the laboratory. Small, solid-state temperature reference units are now available commercially. A typical unit manufactured by Consolidated Airborne Systems, Inc., New Hyde Park, New York, is 3-3/4 in. x 3/4 in. in diameter, weighs less than 80 grams and provides a reference signal accurate to 2°C for ambient temperature variations between -25°C and +100°C. The self-contained power supply has a life expectancy of 10,000 hr in continuous use and 2-3 yr in intermittent use. Precautions must be taken to insure that the temperature reference unit is not exposed to temperatures below -40°C or above +150°C, or the power supply batteries contained in the unit may be damaged.

Because commercially available reference junctions show a drift in reference temperature with changes in ambient temperatures, a fixed ambient should be provided for optimum results. Although thermocouple outputs are characteristically low, they can be increased by selecting a high-reference junction temperature. With a 550°C reference temperature, chromel-alumel thermocouples give signals of the order of 22 mv. Sensitivity of the device is reduced correspondingly. The reference temperature is created electronically within the reference junction unit. Units are available with output impedances of 20 to 10,000 ohms.

Voltage output levels are on the order of 40 μv/°C for copper-constantan. Readout can be by means of a potentiometer circuit or a series millivoltmeter circuit, with the latter offering considerably reduced accuracy.

Resistance thermometers utilize small elements of fine wire of a type, commonly platinum, that has a high temperature coefficient of resistance. The element usually is connected as one arm of a resistance bridge. The output voltage of the bridge varies with bridge unbalance changes due to the resistance variation of the element with temperature. A bias voltage of 10 to 20 v is adequate, and usually only a few milliwatts of power are used. The surface temperature loop (No. 54) was suggested to consist of 0.003-in. diameter platinum wire which would have a resistance of about 10 ohms for a 10-ft loop. Care must be taken that strains are not induced in the wire with temperature changes since these will result also in resistance changes. Durable temperature compensated leads should be provided to the element, long enough to allow for a reasonable separation from the instrumentation. The temperature coefficient of platinum is about 0.3 per cent/°C.

Thermistor elements are usually brittle beads, disks, rods, wafers, etc., of a metal oxide semiconductor material whose resistance decreases exponentially with increasing temperature. The coefficient for these types is about -4 per cent/°C. Single crystal SiC types (coefficient about -2 per cent/°C) and positive coefficient single crystal Si types (coefficient about 0.7 per cent/°C) are now available. All types are used in a resistance bridge as for a resistance thermometer.

Thermocouples and platinum resistance elements would be only slightly affected by expected levels of space radiation. Thermistors, except for the SiC types, are in general quite sensitive to radiation.

Principal development problems are reference junction protection and a surface temperature-sensing device. These difficulties are with technique, not concept, and can be resolved with a directed effort.

No. 56, 57. Thermal Conductivity Probes

Thermal conductivity probes described are based on a transient technique wherein the temperature field in the material surrounding a line source of heat is monitored and thermal conductivity calculated from the rate of rise. The probe has been described in the literature, and the theory is well established (Wechsler et al., 1963). Commercial probes vary in dimension from about 0.030 to 0.375 in. in diameter and 3 to 30 in. in length. Those for lunar use probably will be of the smaller diameter and length.

Probes should be capable of measuring materials with conductivities from about 2×10^{-6} w/cm°K to about 1 w/cm°K. The accuracy of probe measurements has been reported to be about ±3 per cent; however, with the limited data to be obtained (several temperatures rather than a complete temperature-time history), accuracies in the order of ±10 per cent to ±15 per cent are expected. The reproducibility from test to test should be somewhat more accurate, so that actual changes in material properties as a function of time can be measured. Successive probe measurements can be made as soon as the probe returns to thermal equilibrium with the surroundings (between 1 and 10 hr for most materials).

Power requirements for probes are relatively small. For low thermal conductivity material, typical power inputs may be about 20 mw for the measurement period of 1 hr. For a rock system, a power of 100 mw for a 10-min duration may be required. The resistance of the probe heater can be varied to accommodate most voltage sources from about 1 to 20 v. The output of the instrument will be a voltage of between 0 and 0.4 mv. Since absolute temperature measurements are not essential for the probe measurement, any convenient reference junction for the thermocouple may be used, e.g., a block of large thermal mass, the lunar subsurface material, etc.

Choice between thermistors and thermocouple-type probes will depend on interactions with other instrumentation and trade-offs in sensitivity, accuracy and speed of response. Two probes are considered for the instrument evaluation: one for insertion into the lunar surface by the astronaut, and a heavier probe mounted on the LEM landing gear. The first will be usable only if a dust layer of adequate depth is found or if insertion into a crevice or crack is possible. The latter case would permit subsurface temperature measurement, but thermal conductivity data would be inaccurate due to probable poor thermal contact with the surrounding material. The second device would measure the thermal conductivity of the surface material under a LEM landing gear pad.

In theory, thermal diffusivity can be calculated from measurements made with the thermal conductivity probe. Difficulties encountered with this technique are: (1) it is necessary to know the radial position of the temperature sensor accurately or to calibrate the probe with materials of known thermal diffusivity similar to that of lunar materials, which is not known; and (2) the contact resistance between the probe and the material measured produces greater errors in measuring diffusivity than in thermal conductivity measurements.

Thermal diffusivity estimates also can be obtained from measurements of thermal conductivity, density and indications of specific heat from compositional analysis of the lunar materials.

It has been assumed, despite these difficulties, that this method will be used for subsurface thermal diffusivity measurements.

No. 58. Modified Flash Radiometer

This is a conceptual instrument to measure surface thermal diffusivity without disturbing surface materials. The experimental apparatus would consist of an optical system, for instance mounted on a tripod, that focuses a radiation flash from a flash lamp or laser onto a small spot on the lunar surface. This spot, and the region surrounding it, is viewed by an optical system and imaged onto a small array of IR detectors. The optics and detectors are capable of transmitting and detecting out into the far infrared, for example, to 25 microns. As the flash-induced thermal wave progresses with time from the initial flash spot, the wave amplitude, i.e., temperature, is observed as a function of time by the detectors, each of which represents measurement at a different distance from the center of the spot. The information from each of these detectors could be treated as ratios of two readings taken by the same detector but at two different times. Thus, calibration problems, the problems of drifts in the sensitivities of individual detectors and variations from one detector to the next can be largely eliminated. All that must be known is the position (distance) of the spot viewed by each detector with respect to the original flash spot and the time of each measurement. A sketch of the experimental apparatus is shown in Figure V-4.

No. 59. Reflectance Radiometer (Ultraviolet, Visible, Infrared)

The instrument described in Table V-1 is a conceptual, hand-held instrument to be pointed at the surface by the astronaut. Spectral analysis of the emitted and reflected radiation from the surface would be obtained by means of a set of band-pass filters in each of the three spectral regions (UV, visible, IR). Alternatively, a scanning-type instrument could be used, one portion covering the UV-visible region and the other the infrared. The UV-visible spectrometer described previously (No. 16) could be used for this purpose. A similar instrument could be built for the infrared region, or perhaps full capability could be combined into one instrument. Separate detectors probably will be needed for each spectral region.

A design study is needed to determine the best experimental approach to this problem.

No. 60. Heat Flow Meter (Conductive)

Conductive heat flow meters consist of a thin disk containing a multiple thermocouple assembly and a conductive spacer. This type of device produces an emf essentially proportional to the heat flow through the disk. Typical commercial heat flow meters vary in size to about 6 in. in diameter and have outputs of about 2 v for a heat flux of 1 w/cm^2. For typical lunar surface flux values, 0.1 w/cm^2 to 2×10^{-3} w/cm^2, outputs of 4 to 200 mv can be expected. The temperature difference created by the heat flux would be about 14°C for a flux of 1 w/cm^2 and 0.3° for a flux of 0.1 w/cm^2.

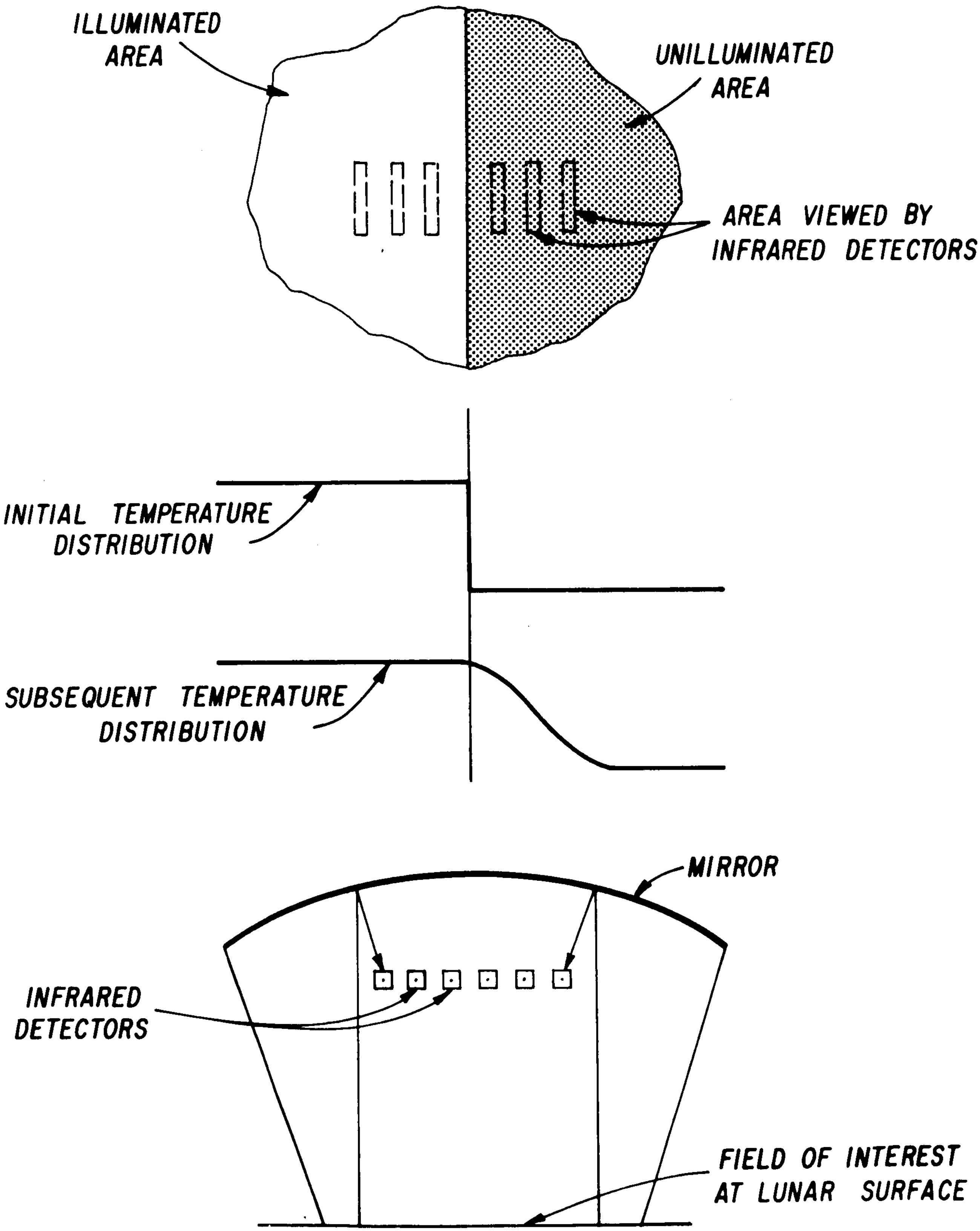

Figure V-4. Method of Measurement of Thermal Diffusivity of Lunar Surface Layers

A secondary characteristic of this type of heat flux meter is that it is somewhat temperature-sensitive. Since the individual thermocouple sensitivity is a function of temperature, the flux meter calibration depends on the absolute temperature of the meter. Typical commercial heat flux meters have temperature coefficients of about 0.3 per cent/°C.

In subsurface use, the conductive heat flow meter, combined with a temperature sensor, is buried at various places beneath the surface. Validity of the measurement requires that the meter be thin compared to the dust or surface layer and have a high conductance compared to the surface material. Errors in heat flow caused by direct flow disturbances of the conductive meter should be less than 10 per cent for most low-conductance material. Errors are much larger for surface emplacement, as discussed in Chapter II. For surface heat flux measurements, the following instrument, a radiometric surface heat flux meter, is the more plausible device.

No. 61. Radiometric Heat Flow Meter

This heat flow meter is a conceptual instrument whose theory of operation is given in detail in Appendix H. The disk should be suspended at a height that is great compared to the disk diameter, and no projecting lunar terrain should be "visible" to the upper side of the disk.

Two modes of operation are possible: one in which only the temperature of the disk is used to determine lunar flux; the other in which a flux disk of the type already discussed is used. Advantage of the first is simplicity. Advantage of the second, in terms of practical instrumentation, is slightly increased accuracy by avoidance of a thermocouple cold junction, or equivalent compensator, that must be maintained at a known temperature.

A reliable and accurate lunar surface flux determination with a built-in self-check is to be obtained by using both schemes, i.e., by using a flux disk containing a temperature sensing element such as a thermocouple or resistance thermometer. The cost is low in terms of additional apparatus (one additional information channel), and the result is a lunar flux determination at a high confidence level.

The fluxes to be measured range from 2×10^{-3} w/cm^2 when the lunar surface is dark and approximately 140°K to 0.1 w/cm^2 when the solar-illumined lunar surface is in the range of 390°K. The accuracy to be achieved in the measurement of each of these flux levels by the system outlined is in the range of ±5 per cent (see Appendix H).

The apparatus (see Figure V-5) consists of a tripod standing on the lunar surface. A horizontal arm extends in one direction. At the end of this arm, a disk is on a vertical suspension that maintains it parallel with

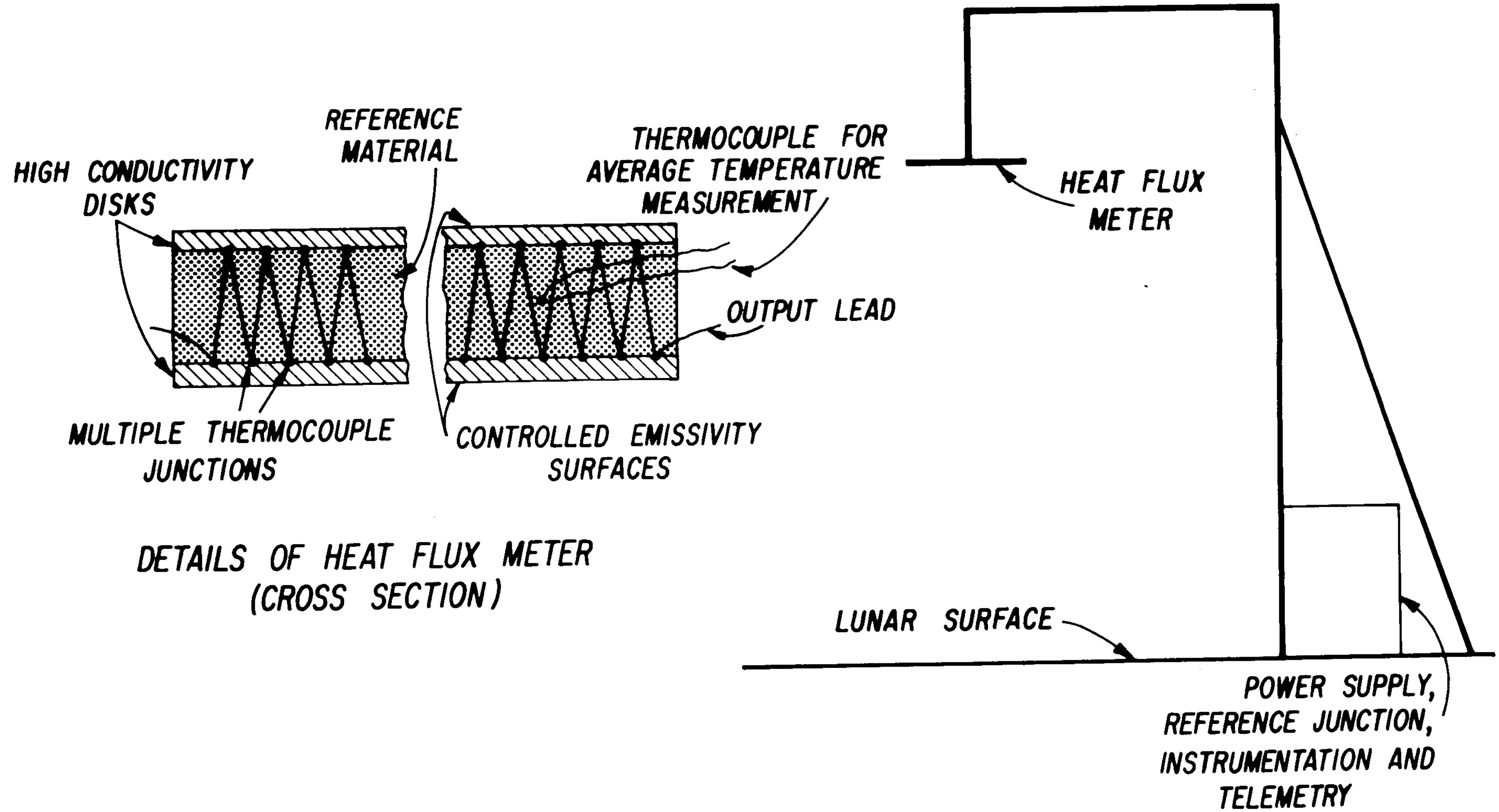

Figure V-5. Apparatus for Measurement of Heat Flux on the Lunar Surface the lunar surface. The tripod might be 2 ft high and the disk 3 in. in diameter and suspended off the ground. The actual configuration and dimensions are a matter to be determined in a design study.

No. 62. Line Source Pressure Gauge

This type of gauge can be made to be sensitive to various gas pressure ranges by varying the particle size of the reference powder. The lower the gas pressure to be studied, the larger the particle size of the reference powder. Practical considerations on particle size, to keep the apparatus small, show that the method is suitable only for pressures above about 10^{-4} torr. Therefore, unless regions of considerable gas pressure exist, this device would be inadequate. Such a gauge could be placed in regions of suspected volcanic activity and, by periodic thermal conductivity measurements of the reference material, gas diffusion or flow could be indicated.

No. 64. Tracking Transducer on LEM TV Camera

The directional receiver on the LEM TV camera is a null-seeking unit, similar in principle to the AN/ARA 25 used to determine aircraft bearing, that develops azimuth error signals according to misalignment of the receiver null axis and the astronaut's transmitter position. The error signals drive null positioning servos to reduce the error signal to zero. Azimuth position is determined by encoders attached to the positioning servo. Positioning accuracy of $1/2°$ of arc will not require complex encoders. Tracking in elevation is not considered since surface reflections would pose formidable problems for using radio frequencies for this purpose.

The transmitter contained in the fixed package transmits an amplitude modulated UHF signal. The astronaut's receiver detects the amplitude modulation and, in turn, modulates and transmits a second UHF signal back to the fixed package. The detected modulation at the LEM is compared to the drive modulation, and the phase difference determines the astronaut's range. Range resolution will depend on the frequencies chosen for modulating the transmitters. Choosing the wavelength λ_m for an electromagnetic wave corresponding to 6000 ft, the modulation frequency that will yield $180°$ phase shift over the 1500-ft range within which the astronaut may move may be established as follows:

$$f_m = c/\lambda_m = 165 \text{ kc}$$

where c = velocity of electromagnetic radiation in ft/sec

f_m = frequency corresponding to λ_m

Modulating the transmitters near 165 kc will yield a range resolution of

$$\frac{1500}{180°} = 8.33 \text{ ft/deg } \phi \text{ shift.}$$

The two transmitters need not be phase-locked or synchronized. In fact, they should operate on different frequencies chosen to minimize cross-coupling effects. Frequency stabilization will not be a stringent requirement. The transmitter carrier frequencies should be between 600 and 1000 mc to avoid interference with the data link on the LEM.

The range information also may be used to control the TV camera zoom capability so that, normally, the area coverage is the same at all ranges. An override control would allow the option of manual control if desired.

Figure V-6 is a simplified block diagram of the system. The estimated weight splits up into 1.5 lb carried by the astronaut and 3 lb attached to the LEM TV camera. About 200 mw of power are required on the astronaut.

No. 66. Sun Compass

A sketch of this instrument as conceived is shown in Figure V-7. Its use to determine true bearing of features in a photograph entails the following determinations and calculations:

APH = apparent pin height. The height of the pin is measured in the photograph against the concentric scale rings.

PH = actual pin height for the particular mission. If the sun is near the horizon, pin height can be shorter.

SL = shadow length. It is measured on the concentric scale rings.

θ_s = altitude of the sun. The altitude of the sun will vary rather slowly because the moon rotates only about 1/2°/hr.

θ_c = altitude of the camera lens. Because of the moon's photometric function, the azimuth angle between sun and camera lens and tilt of the camera relative to the local vertical may be important. The difference in azimuth angle between the sun and the camera in Figure V-7 is 360-270 = 90°.

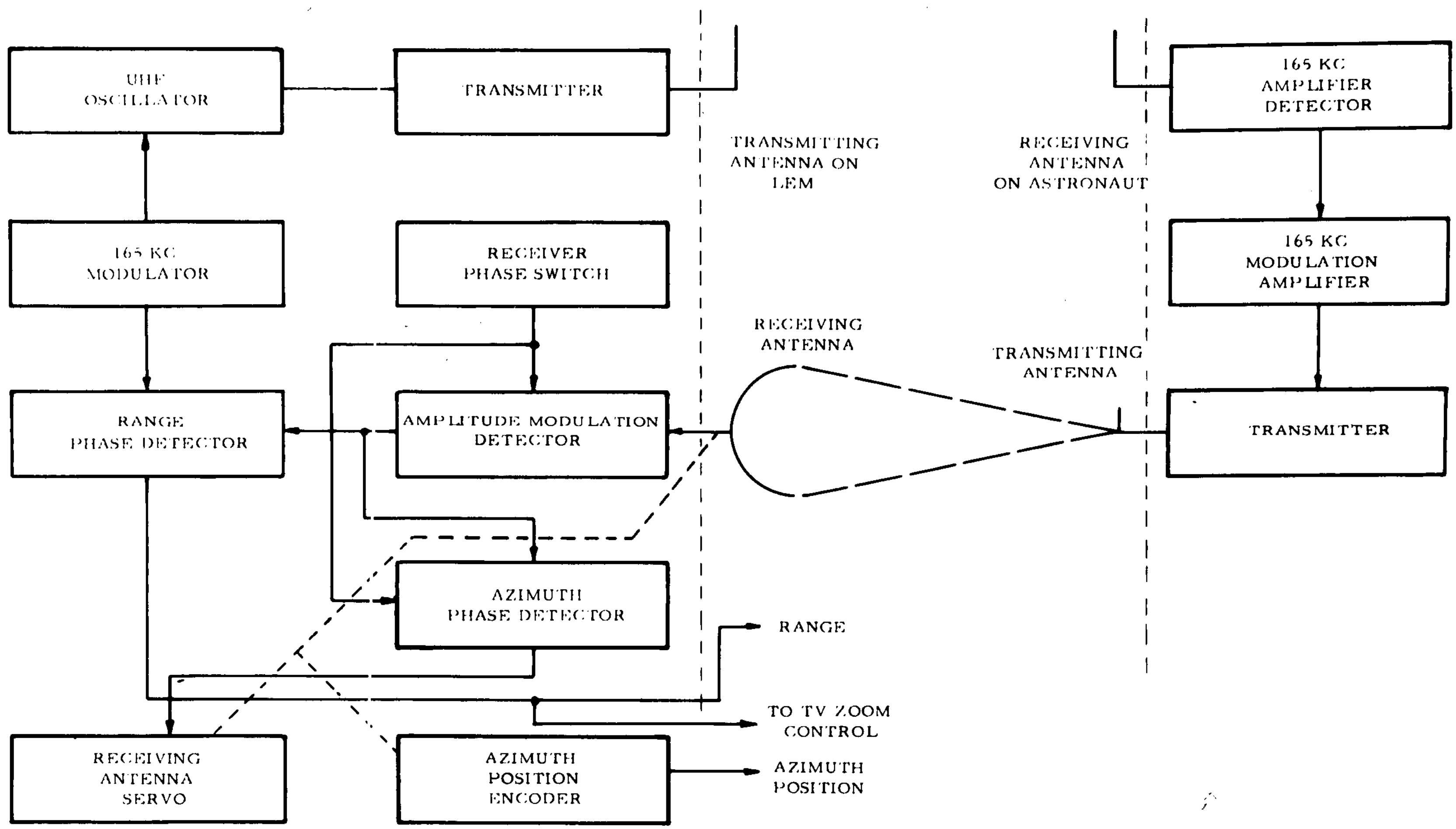

Figure V-6. Simplified Block Diagram of Tracking Transducer for LEM TV Camera.

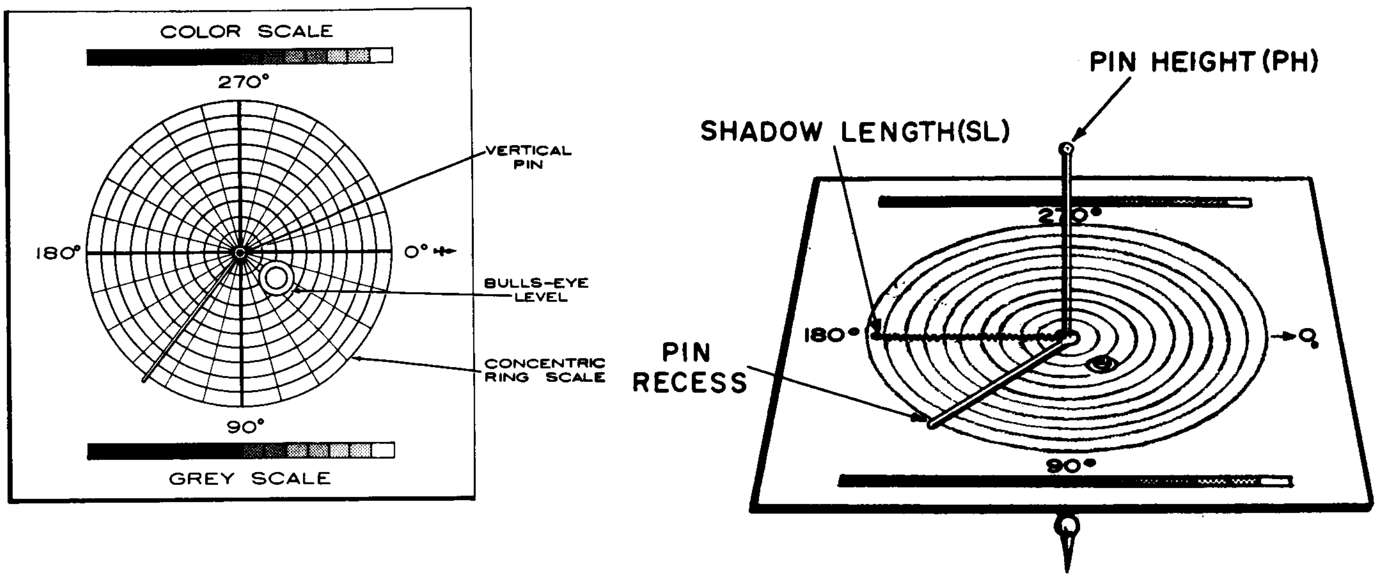

Figure V-7. Sun Compass

Then

$$\text{Tan } \theta_s = PH/SL$$

$$\text{Tan } \theta_c = PH/APH$$

To calculate the true bearing (only 1 to 2° accuracy is needed), the following formula from the Keuffel and Esser Solar Ephemeris (1964) may be used:

$$\text{Cos } Z = \frac{\sin d - \sin \theta_s \sin(\text{lat})}{\cos \theta_s \cos(\text{lat})}$$

where: d = sun's declination
Z = sun's bearing
lat = latitude of observation point

The color and grey scales will help to determine true conditions should color and grey distortion occur by improper developing, incorrect exposure, film damage by radiation, or all three.

No. 67. Night Stadia Targets on LEM

Daytime stadia targets could be painted patterns, or possibly natural features of the LEM could be used from a foreknowledge of their dimensions. Night targets will be needed during lunar day if surveying photographs are made toward the shadowed side.

No. 68. Lunar Hand Camera

The weight estimate for the camera in Table V-1 includes film. The camera is a dual 35-mm with 24 x 36-mm format. Recommended use probably will call for color film in one roll and XR black and white on the other. Current Graflex design has 70 exposures/roll.

The shutter is a focal plane disk with speeds of 1/30 - 1/500 sec. Present focusing arrangement is manual in three steps. Reflex viewer may be desirable for closeup studies. A built-in exposure meter using coupled needle-matching is provided. Film advance is manual or motor-driven.

Needed modifications are a mil scale ahead of the film for accurate gauging of elevation difference and distance to LEM and a level-indicating device.

No. 70. Descent Camera

The camera listed in Table V-1 only partially meets requirements. A film enlarger/printer is included with the camera in the computer instrument evaluation analysis. Location of the camera inside the LEM is desirable so that photomaps of the landing site area can be printed for astronaut use. Cycle rate on the camera is variable from 1/300 milliseconds to 1/3 sec.

Design studies are needed on required film capacity, proper IMC rates and cycle rates and exposure levels.

Desirable mounting inside the LEM may require an optical or mirror viewing arrangement for the camera to "see" below the LEM during descent.

No. 76. Surveyor Soil Mechanics Test Apparatus

Reaction anchors and frame are suggested as modification to this instrument. These will provide greater reaction force than can be obtained by instrument and astronaut weight under lunar gravity conditions. Force is monitored by strain gauge bridges and displacement by potentiometer displacement transducers.

Considerable modification may be necessary to adapt present Surveyor design to portable use by astronauts. Screw augers are one possible approach to reaction anchors.

No. 78. Vane Shear Tester

Adaptation of the commercial instrument for lunar use would stress miniaturization. A hand-operated device is envisioned, with torque reaction supplied by the astronaut.

No. 81, 82, 83. Sampling Tool Packages

These packages and the individual items in them are discussed in detail in Chapter IV, Section B.

E. SCIENTIFIC INSTRUMENT PACKAGES

Certain of the recommended instruments and associated measurements discussed in Part I, Chapter II, to yield significant data, must be incorporated in unattended scientific instrument packages (SIP). A package is to be left on the lunar surface and operated continuously or periodically over extended periods of time. This section discusses the design of the SIP and the method used to arrive at an estimate of the total payload cost in terms of the weight and volume of the SIP and its associated control and telemetry systems and power supply.

1. SIP for First Flight, Alternatives I and II

a. Components of the SIP

Instrument components of the recommended scientific instrument package for the first APOLLO flight are listed in Table V-2 together with their weight, volume and power requirements.

TABLE V-2

RECOMMENDED SCIENTIFIC INSTRUMENT PACKAGE

Flight I, Alternative I (one egress of 2-hr duration):	Weight (lb)	Volume (in.^{3})	Power (watts) Operate	Power (watts) Standby
Transponder	2.0	35	1	0.10
Combination LP, SP seismometer and tidal gravimeter	32.0	1400	0.65	0.65
Helium magnetometer (3-axis)	6.3	220	7	0.00
Survey rate meter	1.0	70	0.10	0.10
Total	41.3	1725	8.75 Peak	0.85 Continuous

Flight I, Alternative II (two egresses, 2 and 2.5-hr duration, respectively):	Weight (lb)	Volume (in.^{3})	Power (watts) Operate	Power (watts) Standby
Alternative I SIP	41.3	1725	8.75	0.85
Platinum resistance thermometer loop	0.2	2	0.015	0.00
Thermal conductivity probe	0.4	4	0.01 to 1.0	0.00
Total	41.9	1731	8.8 Peak	0.85 Continuous

These instruments or items of equipment are discussed in detail in the preceding section of this chapter as Items No. 72, 45, 39, 30, 54, and 56, respectively.

b. Telemetry Requirements

To estimate telemetry requirements for this package, it was necessary first to determine the rate of data acquisition per instrument, or per channel, the number of channels and the peak rate of data acquisition for all channels which must operate simultaneously. The following discussion gives only a first estimate of telemetry requirements. A detailed design study will be required to determine actual requirements and to optimize performance. Estimates of data rates are given in Table V-3.

TABLE V-3

DATA RATES FOR SIP INSTRUMENTS

Combination seismometer:	Word Size	Sampling Rate	No. Channels	Rate (bits/sec)
Short-period noise	6 bits + sign	20/sec	1	140
Long-period noise	6 bits + sign	1/sec	3	21
Tidal gravity	8 bits + sign	2/day	1	negligible
Helium magnetometer:				
Magnetic field	6 bits + sign	2/sec	3	42
Survey rate meter:				
Particulate radiation flux	17 bits	1/hr	1	negligible
Platinum resistance thermometer loop:				
Surface temperature	8 bits + sign	2/day	1	negligible
Thermal conductivity probe:				
Subsurface temperature, thermal conductivity	8 bits + sign	2/day	1	negligible
		Total channels	11	
			Peak Data Rate	203

The Alternative II SIP is used for these estimates since the two items added for that version contribute only negligibly to the data rate. The transponder is not included since its transmitter is self-contained. In addition to the 11 scientific data channels, approximately 20 engineering data channels will be required for monitoring instrument operation calibration. The data rate on these channels would be low since they are sampled only at infrequent intervals and can be sequenced by programming to be noncoincident with the scientific data channels.

The peak data rate shown in Table V-3 actually is misleading because the short-period seismometer, which is the dominant contributor to the data rate, can be activated by command or programmed. Thus, its data output can be sequenced with that of other instruments. Further, since a data run of only 5-15 min at a time would be required, the transmitter can be monitored continuously during that period. Hence, data storage capacity need be no greater than that of state-of-the-art buffer storage units. The peak data rate of concern then is only 63 bits/sec. The number of buffer storage units provided will be adequate so that interrogation will only be required at intervals of about 40 min.

The required component parts of the telemetry system are listed in Table V-4, together with their estimated weight, volume and power requirements. The buffer storage units are used in preference to a tape recorder in order to reduce payload requirements. Their use is made possible, as just discussed, by the relatively low data-collection rate. The use of a program control unit and command unit increases flexibility substantially, allowing engineering checks and scientific measurements by programmed sequencing or on command. The helium magnetometer, which has the greatest power requirement of any instrument component of the SIP, thus can be turned on by command in order to reduce energy requirements to be satisfied by the power supply.

The telemetry system is capable of timing the arrival of solar flares in a few microseconds. If seismic activity were being monitored when a flare occurred, the seismic data would have to be stored until the data communication link was again available.

Telemetry data link parameters are based on a coherent PCM/PSK/PM system. The 2-w transmitter (input power) is adequate to be received by the 35-ft antennas in the APOLLO communication and instrumentation network at the information rates projected. The proposed transmitter information bit rate capacity of 10^3 bit/sec would be roughly equivalent to a 1 kc bandwidth.

Some consideration was given to using the antenna from the LEM TV-system for the SIP telemetry system. This would, however, entail a last-minute traverse by the astronaut to transfer the antenna from near the LEM to the SIP site and would be very costly in terms of astronaut time during early APOLLO missions. In addition, this procedure would prevent checkout of the SIP until just prior to the return trip launch phase and allow no time for corrective measures or repairs. The saving in weight and volume was not deemed sufficient to justify the offsetting penalties.

TABLE V-4

SIP TELEMETRY REQUIREMENTS

	Weight (lb)	Volume (in.^{3})	Power (watts) Operate	Power (watts) Standby
Encoder (40 channel)	10	150	6	0
Buffer storage (four wire units @ 50 x 10^3 bits each)	11	425	2	0.4
Program control unit (w/core memory)	5	150	16	2.2
Command unit (receiver, demodulator/decoder)	8	200	6	0.2
Power converter/regulator	6	160	22	2.0
Transmitter (10^3 bit/sec, two for redundancy)	4	120	2	0
Antenna (2-ft parabolic, folded)	4	500	0	0
Total	48	1705	54 Peak	4.8 Continuous

c. Energy Requirements

Energy requirements were first calculated on the basis of a power supply consisting of secondary batteries recharged by an unsteered solar array. The unsteered array would have a cosine law response to the solar energy incident on the moon. Hence, it was assumed that the batteries would have to supply required power for the duration of a lunar night (~ 14.75 days) plus approximately one day to allow for the near-zero output at the beginning and end of the lunar day due to the cosine law response. A different geometric configuration might permit a more ideal response with minor payload cost. Batteries would be charged at the start of the mission so that power would be available to the SIP immediately upon activation.

Energy requirements for the 15.75-day period were estimated as shown in Table V-5. For active operation of equipment, the difference between the operating power and standby power is used since the total standby energy requirements are calculated separately.

TABLE V-5

ENERGY REQUIREMENTS FOR SIP INSTRUMENTS

AND TELEMETRY SYSTEM

Equipment	Power (watts)	Time	Energy (watt-hr)
Standby (continuous power):			
Instruments	0.85	15.75 days	321.3
Telemetry and control system	4.8	15.75 days	1814.4
Transponder (transmits only on command, 100 transmissions)	0.9	10 sec/transmissions	0.25
Magnetometer	7.0	2 min/day + one 12-hr run	87.7
Encoder, buffer	7.6	20 hr	152.0
Command unit	5.8	10 min/day	15.2
Program control unit	13.8	10 min/day	36.2
Transmitter (2×10^6 total bits @ 10^3 bits/sec)	2.0	1 hr	2.0
Heater power for thermal control	1.0 (avg)	15.75 days	378.0
Subtotal			2807.05
Power converter/regulator (assume 65% efficiency on energy exclusive of standby)			361.5
Total			3168.55

Using projected conversion factors of 50 w-hr/lb and 3 w-hr/in.^{3} (silver-zinc batteries, Space/Aeronautics R & D Handbook, 1962-1963), a secondary battery pack weighing 63.4 lb and occupying 1060 in.^{3} is indicated.

The required power output from a solar cell array in order to recharge the battery pack during a lunar day may be calculated as follows:

$$p_o = \pi \frac{(\text{total energy})}{T} = \pi \frac{3169 \text{ w-hr}}{708 \text{ hr}} \cong 14 \text{ w} \quad (1)$$

where:

p_o = array output power at normal incidence of solar energy

T = lunar diurnal period

Using conversion factors of 8w/ft^2 and 3.2 w/lb (Space/Aeronautics R & D Technical Handbook, 1962-63), the array would weigh 4.4 lb and have an area of 1.75 ft^2. Assuming a thickness of 1 in. for the solar cell panel, this indicates a volume of 252 in.^{3}.

Total weight and volume requirements of the SIP power supply then are:

Battery pack	63.4 lb	1060 in.^{3}
Solar cell array	4.4 lb	252 in.^{3}
Total	67.8 lb	1312 in.^{3}

A possible alternative to the solar cell secondary battery approach to the power supply would be a nuclear or radioisotope power source. If there is a large disparity in peak and standby power for the recommended SIP system, this may exact a heavy penalty in weight, as the nuclear power source has to be capable of delivering peak power when needed. During standby periods, the power source would have a large overcapacity. Projected conversion factors for radioisotope power sources are 1 w/lb (Space/Aeronautics R & D Handbook, 1962-63) and 0.008 w/in.^{3} (by extrapolation from the SNAP-9A power supply) which would indicate a weight of 62.8 lb and a volume of 7850 in.^{3} for the SIP system.

The radioisotopic power supply estimates are based on capacity to supply full peak load continuously and must be considered a "worst case" estimate. The use of a rechargable battery pack as a "topping" unit would permit reduction in payload requirements by reducing the continuous power output required. The battery pack would supply power only during peak load periods, which are estimated at most as 20 hr in duration. Hence, it would be considerably lighter than the battery pack required for the duration of the lunar night.

Although the size and weight requirements with this approach will be reduced, the radioisotope power supply will probably occupy more volume than a battery pack/solar cell array. One disadvantage of the radioisotope power supply, present in any combination, is the generation of heat which either must be rejected or used for thermal control purposes. The presence of this heat will be a serious problem in LEM design.

Weight requirements for the two power supply alternatives are comparable, but volume requirements for the radioisotope supply are considerably greater than for the battery pack/solar cell array. It is shown below, under packaging and thermal control, that total payload requirements using the radioisotope power supply fall within the constraints for both alternatives of Flight I. With the battery pack/solar cell array, requirements for Alternative II fall slightly outside the weight constraint. Because of its significantly smaller volume, the recommended power supply for Alternative I is the battery pack/solar cell array. The radioisotope power supply is recommended for Alternative II in order to stay within the weight constraint.

The indicated difference in weight between these two power supply alternatives is felt to be less than the accuracy of the estimates. The considerably smaller volume of the battery pack/solar cell array is clearly an important trade-off in the final system design. Choice of power supply, therefore, probably should remain until a detailed design study of the SIP is concluded.

d. Packaging and Thermal Control

Lacking a specific design for the SIP, it is difficult to discuss packaging and thermal control problems in detail. For the purposes of this study, therefore, additional percentage factors, (discussed in Section C of this chapter) of 20 per cent in weight and 25 per cent in volume were allocated for packaging (including cabling) and thermal control requirements in the analysis of the SIP and other instruments. The allocation factors do not include power supply requirements for any active thermal control. Such requirements already have been included in previously calculated energy requirements.

Weight and volume requirements for the SIP included in Flight I, Alternatives I and II, are given in Tables V-6 and V-7. The requirements are based on using either a battery pack/solar cell power supply or a radioisotope power source. Total instrumentation weights and volumes also are given for reference to the originally specified maximum weights and volumes:

Total weight -- 250 lb (40-80 lb in LEM ascent stage and and 210-170 lb in LEM descent stage)

TABLE V-6

TOTAL INSTRUMENTATION REQUIREMENTS, FLIGHT I, ALTERNATIVE I

A. With Battery Pack/Solar Cell Power Supply		WEIGHT (lb)		VOLUME (in.^{3})
SIP instruments (see Table V-2)		41.3		1,725
Telemetry and control system (see Table V-4)		48.0		1,705
Battery pack/solar cell power supply		67.8		1,312
		157.1		4,742
Packaging and thermal control factor (20% weight, 25% volume)		31.4		1,185
SIP total		188.5		5,927
Other instruments and kits				
Descent camera and printer	9.0		550	
Personal dosimeters (2)	0.6		2	
LEM survey rate meter	1.0		70	
Landing gear thermometer	0.5		4	
Chemical reactivity detector	0.5		17	
Boot thermometer	0.5		4	
Camera and flash	5.3		90	
Staff penetrometer	2.5		20	
Tracking transducer	4.5		150	
Gravity meter	7.0		450	
Sample culture pH readout	1.2		28	
Sampling kit (6 vac, 26 bags)	10.7		250	
Geology kit	7.0		46	
Subtotal	50.3		1,681	
Packaging and thermal control	10.1		420	
Subtotal	60.4	60.4	2,101	2,101
Grand total		248.9		8,028
B. With Radioisotope Power Supply				
SIP instruments (see Table V-2)		41.3		1,725
Telemetry and control system (see Table V-4)		48.0		1,705
Radioisotope power supply		62.8		7,850
Subtotal		152.1		11,280
Packaging and thermal control factor		30.4		2,820
SIP total		182.5		14,100
Other instruments and kits (see A above)	50.3		1,681	
Packaging and thermal control factor	10.1		420	
Subtotal	60.4	60.4	2,101	2,101
Grand Total		242.9		16,201

TABLE V-7

TOTAL INSTRUMENTATION REQUIREMENTS FLIGHT I, ALTERNATIVE II

		WEIGHT (lb)		VOLUME (in.^{3})
A. With Battery Pack/Solar Cell Power Supply				
SIP instruments (see Table V-2)		41.9		1,731
Telemetry and control system (see Table V-4)		48.0		1,705
Battery pack/solar cell power supply		67.8		1,312
		157.7		4,748
Packaging and thermal control factor (20% weight, 25% volume)		31.5		1,187
SIP total		189.2		5,935
Other instruments and kits				
Descent camera and printer	9.0		550	
Personal dosimeters (2)	0.6		2	
LEM survey rate meter	1.0		70	
Landing gear thermometer	0.5		4	
Chemical reactivity detector	0.5		17	
Boot thermometer	0.5		4	
Camera and flash	5.3		90	
Extra film	1.0		20	
Extra flash attachment battery	0.8		4	
Staff penetrometer	2.5		20	
Tracking transducer	4.5		150	
Gravity meter	7.0		450	
Sample culture pH readout	1.2		28	
Sampling kit (5 vac., 2 mech., 24 bags)	12.8		323	
Geology kit	7.0		46	
Reflectance radiometer	8.0		150	
Susceptibility bridge	0.7		18	
Subtotal	62.9		1,946	
Packaging and thermal control factor	12.6		487	
Subtotal	75.5	75.5	2,433	2,433
Grand Total		264.7		8,368
B. With Radioisotope Power Supply				
SIP instruments (see Table V-2)		41.9		1,731
Telemetry and control system (see Table V-4)		48.0		1,705
Radioisotope power supply		62.8		7,850
Subtotal		152.7		11,286
Packaging and thermal control factor		30.5		2,822
SIP total		183.2		14,108
Other instruments and kits (see A above)	62.9		1,946	
Packaging and thermal control factor	12.6		489	
Subtotal	75.5	75.5	2,433	2,433
Grand total		258.7		16,451
Delete gravity meter and its packaging and thermal control factor*		-8.4		-563
Revised Grand Total		250.3		15,978

*Deleting the gravity meter frees 5 min of the astronaut's time which may be used for sampling and/or visual observations.

Total volume -- 10 ft^3 (17,280 $in.^3$) in three packages [one 2-ft^3 (3456-$in.^3$) package in the LEM ascent stage and two 4-ft^3 (6912-$in.^3$) pie-shaped, packages in the LEM descent stage]

These total weight and volume constraints are met for Flight I, Alternative I, by using either power supply. Although using a radioisotope power supply results in a 6-lb lighter SIP and total package weight, supplying power by a battery pack/solar cell array yields a package volume only one-half as large. These results indicate that, for Flight I, Alternative I, the SIP should be powered by a battery pack/solar cell array unless studies of other subsystems of the LEM indicate that weight rather than volume is at a premium. If the latter is indicated, the radioisotope power supply may be used.

For Flight I, Alternative II, the specified total weight is exceeded for the instruments listed in Table V-7. Removing the gravity meter from the package powered by the radioisotope source reduces the package weight to 250.3 lb. This variance of weight from the constraint is well within the sum of individual estimate accuracies for each instrument. The 5 min allotted to operation of the gravity meter may be used for sampling and/or visual observations. The total weight of the package powered by the battery pack/solar cell array also may be brought within specifications by removing both the gravity meter and the reflectance radiometer. However, removing both instruments would free 20 min of the astronaut's time. Accordingly, the package powered by a radioisotope source is recommended on the basis of these results.

From the previous discussion, two package configurations, depending on the power supply, evolve for Flight I, Alternative I, and one configuration for Flight I, Alternative II. In approaching the packaging problem, the primary consideration besides weight and volume constraints, is that the instruments of the SIP be located in the LEM descent stage. This not only permits the instruments to be integrated into a complete package but facilitates removal and handling of the SIP from the LEM. The desirability of locating other instruments in either the ascent or descent stage of the LEM has been discussed in Section C of this chapter. An additional packaging constraint was assumed -- the total weight of the instruments packaged in the LEM ascent stage is to be as near as possible to the lower limit of the specified 40 to 80-lb range.

Summaries of the three possible packaging configurations are listed in Tables V-8, 9 and 10.

TABLE V-8

INSTRUMENT LOCATION, FLIGHT I, ALTERNATIVE I, WITH BATTERY PACK/SOLAR CELL POWER SUPPLY

		WEIGHT (lb)		VOLUME (in.^{3})
LEM Ascent Stage				
Descent camera and printer		9.0		550
Personal dosimeters (2)		0.6		2
LEM survey rate meter		1.0		70
Landing gear thermometer		0.5		4
Chemical reactivity detector		0.5		17
Boot thermometer		0.5		4
Tracking transducer		4.5		150
Sample culture pH readout		1.2		28
Sampling kit (6 vac., 26 bags)		10.7		250
Geology kit		7.0		46
Subtotal		35.5		1121
Packaging and thermal control factor (20% weight, 25% volume)		7.1		280
Total (ascent stage)		42.6		1401
LEM Descent Stage				
SIP total		188.5		5927
Other instruments				
Camera and flash	5.3		90	
Staff penetrometer	2.5		20	
Gravity meter	7.0		450	
Subtotal	14.8		560	
Packaging and thermal control factor	3.0		140	
Subtotal	17.8	17.8	700	700
Total (descent stage)		206.3		6627

For Flight I, Alternative I, with a battery pack/solar cell power supply, the totals in Table V-8 indicate that 42.6 lb of instruments and kits are packaged in the LEM ascent stage and that they require only 1401 in.^{3} of the allocated 3456 in.^{3}. Moreover, the volume requirements (6615 in.^{3}) of the SIP and three other instruments located in the LEM descent stage can be packaged in one of the 4-ft^3 (6912-in.^{3}) compartments specified originally. Package design will be greatly simplified if only one compartment of the descent stage is used.

TABLE V-9

INSTRUMENT LOCATION, FLIGHT I, ALTERNATIVE I, WITH RADIOISOTOPE POWER SUPPLY

		Weight (lb)		Volume (in.^{3})
LEM Ascent Stage				
(same instruments and kits as in Alternative I, with battery pack/solar cell power supply, see Table V-8)				
Total (ascent stage)		42.6		1,401
LEM Descent Stage				
SIP total		182.5		14,100
Other instruments				
Camera and flash	5.3		90	
Staff penetrometer	2.5		20	
Gravity meter	7.0		450	
Subtotal	14.8		560	
Packaging and thermal control factor (20% weight, 25% volume)	3.0		140	
Subtotal	17.8	17.8	700	700
Total (descent stage)		200.3		14,801

The same instruments and kits would be packaged in the LEM ascent stage if a radioisotope power supply were used for Flight I, Alternative I. However, due to the greater volume requirements for the power supply, the estimated volume (14,788 in.^{3}) required by the SIP and three other instruments packaged in the descent stage exceeds the originally specified volume (13,824 in.^{3}). Relocating the penetrometer, camera and flash, and gravity meter to the ascent stage would result in an estimated volume requirement of 14,100 in.^{3} for the descent stage, which still exceeds the originally specified value. Since the total volume is within the constraint, this packaging problem may be solved by a reallocation of volume between ascent and descent stages.

TABLE V-10

INSTRUMENT LOCATION, FLIGHT I, ALTERNATIVE II, WITH RADIOISOTOPE POWER SUPPLY

		Weight (lb)		Volume (in.^{3})
LEM Ascent Stage				
Descent camera and printer		9.0		550
Personal dosimeters (2)		0.6		2
LEM survey rate meter		1.0		70
Landing gear thermometer		0.5		4
Chemical reactivity detector		0.5		17
Boot thermometer		0.5		4
Tracking transducer		4.5		150
Sample culture pH readout		1.2		28
Sampling kit (5 vac., 2 mech., 24 bags)		12.8		323
Geology kit		7.0		46
Subtotal		37.6		1,194
Packaging and thermal control factor (20% weight, 25% volume)		7.5		298
Total (ascent stage)		45.1		1,492
LEM Descent Stage				
SIP total		183.2		14,108
Other instruments				
Camera and flash	5.3		90	
Extra film	1.0		20	
Extra flash attachment battery	0.8		4	
Staff Penetrometer	2.5		20	
Reflectance radiometer	8.0		150	
Susceptibility bridge	0.7		18	
Subtotal	18.3		302	
Packaging and thermal control factor	3.7		76	
Subtotal	22.0	22.0	378	378
Total (descent stage)		205.2		14,486

The radioisotope power supply (7850 in.^{3} plus 25 per cent allowance for packaging the thermal control or 9813 in.^{3} total) could be one package if one compartment of the descent stage were enlarged, and the instruments (4975 in.^{3}) could be packaged in another compartment of the descent stage. This arrangement is clearly inferior to the 1-package configuration in the descent stage obtained by using a battery pack/solar cell array.

The packaging problem for Flight I, Alternative II, must be solved in the same manner because the battery pack/solar cell powered package is too heavy. The resulting package breakdown is one package in the LEM ascent stage (45.1 lb, 1942 in.^{3}) and two packages in the descent stage (radioisotope power supply, 75.3 lb, 9813 in.^{3}; scientific instruments, telemetry and control system, 107.9 lb, 4673 in.^{3}).

Until a detailed design study can be made, the battery pack/solar cell power supply is recommended for Flight I, Alternative I, and a radioisotope power supply for Alternative II.

2. SIP for Second and Third Flights

a. Second Flight

No scientific instrument package is carried on either alternative of the second flight. Emphasis is placed on hazard studies and geologic and sampling operations. Instruments included on the flight do not require time-series data over a period longer than the stay-time of the astronaut on the moon.

b. Third Flight

The SIP recommended for the third flight is intended to permit time-series measurements considered important but not included on the first flight. Recommended instruments for the SIP are shown on Table V-11. The weight and volume estimates on the Table include instrument power requirements. Weight, volume and time requirements proposed for the third flight are shown on Table II-10, Part I.

Telemetry requirements of the SIP are similar to those of the first flight, except that data accumulation rates are much lower. This allows reduction of buffer storage capacity from four 50 x 10^3 bit units to two such units. Further, there is no necessity for a long data run on any instrument (such as allowed for the seismometer and magnetometer in the SIP of Flight I) thus reducing the operating time for some components of the telemetry system. In addition, thermal control requirements are not as severe, permitting a reduced estimate of heater power for thermal control.

Total requirements, shown on Table II-10, for the instruments, telemetry system and power supply for the SIP package are:

	Weight (lb)	Volume (in.^{3})
SIP instruments	29.2	1837
Telemetry system	42.5	1500
Telemetry system power supply	40.0	730
Totals	111.7	4067

TABLE V-11

RECOMMENDED SCIENTIFIC INSTRUMENT PACKAGE

Flight III
(Four egresses, one of 2 hr, three of 2.5 hr.)

	Weight (lb)	Volume (in.^{3})	Time (min)
Line source pressure gauge (subsurface interstitial gas pressure)	1.5	15	40
Thermal conductivity probe; string of 6 platinum resistance thermometers (subsurface heat flow temperature)	0.8	8	40
Micrometeoroid flux and ejecta detector	27.0	1800	15
Radiometric heat flow meter	0.7	12	15
Surface temperature loop	0.2	2	12
Total	29.2	1837	122

3. SIP Design Considerations

The more important lunar environmental constraints were discussed in general terms previously. Of specific importance to the design of the SIP, as well as to the other packages located in the LEM, is the dynamic environment to which it is subjected. The dynamic environment may be considered in two parts: transportation from earth launch to lunar landing; and actual operation. Design of the SIP to meet the former would follow well-established methods. The natural frequency of the SIP must be well above that of the LEM structure to prevent the SIP from acting as a dynamic absorber for the primary LEM structure. Long slender packages, actuating and locking mechanisms, and critical components such as the sensor for the helium magnetometer must be given special attention. The dynamic environment is much less severe during standby and operate modes than during transportation.

Another important design consideration of the SIP is its thermal environment. Here again, the environment may be separated into two parts: transportation and operation. The SIP is not placed on standby until after the LEM has landed on the lunar surface. Thus, equipment bays housing the SIP must be thermally controlled to meet thermal specifications of 0 to +160° F. Only two instruments located in the LEM, the descent camera and one of the survey rate meters (0.1-w continuous power), are operated prior to lunar landing.

The heat dissipated by operation of the SIP will be lost almost entirely by radiation, so all components must perform reliably at temperatures well above those of the surface to which they are radiating heat.

Temperature ranges specified for several instruments of the SIP are given in Table V-12.

Other electrical components of the SIP not tabulated must meet a -20 to + 65° C temperature specification. Some hardware items such as the sampling kit are obviously not critical. The most stringent thermal requirement is specified for the combination seismometer. This is discussed later in some detail.

TABLE V-12

THERMAL SPECIFICATIONS FOR THE SIP

Instrument	Temperature Limits
Combination seismometer	± 20° C around a midpoint between 0 and + 80° C
Helium magnetometer	-20 to +65° C
Sensor for magnetometer	-55 to +55° C
Silver-zinc batteries	0 to 165° F

During the lunar night, heat may be dissipated easily to outer space (-460° F) or to the lunar surface. In fact, it probably will be necessary to add additional heat to maintain the SIP within the specified temperature limits. However, this would involve trade-off studies of weight, power and volume between additional heater requirement and increased insulation thickness. If the SIP uses a radioisotope power source, reactor waste heat could provide thermal control with negligible weight and volume penalties.

During the lunar day, radiation from the lunar surface is more serious than radiation directly from the sun. Accordingly, and as far as practical, the largest exterior surfaces of the SIP should be parallel to the lunar surface and the package insulated from it.

Since the most severe thermal conditions for any instruments of the SIP are specified for the combination seismometer (Table V-11), its thermal control analyses will be illustrated (Lamont Geological Observatory, 1962). A similar analysis may be made for the complete SIP. Figure V-8 illustrates the recommended method for controlling the temperature of the seismometer. It consists of an insulated, truncated, conical, outer shield. The instrument is encapsulated with the same insulation, a layered aluminized mylar. Overall insulation thickness of 1/2 in. gives overall conductance of 0.5×10^{-3} mw/°K cm^2 for the best compromise between shield efficiency and weight.

Results of an analog computer study indicated that, with these passive measures, the instrument would attain thermal equilibrium ($\sim 70°C \pm 20°C$) after two lunar cycles for an assumed initial temperature of 25° C. Lower initial temperatures would require a longer time to reach thermal equilibrium. The temperature fluctuations may be reduced further by using additional heat dissipation and, as a result, a 2-w peak heater is recommended for inclusion in the seismometer package. This inclusion will further compensate for the unknown thermal characteristics of the lunar surface.

For purposes of this study, a 1-w (average) heater power was assumed to be adequate to reduce the seismometer's temperature fluctuations and provide additional thermal control for the SIP as required.

4. SIP Emplacement

a. SIP Transport

Emplacement of the SIP by the astronaut will occur on his first egress and excursion. It must be well removed from the blast area to prevent damage during the LEM ascent launch phase. Hence, it probably will

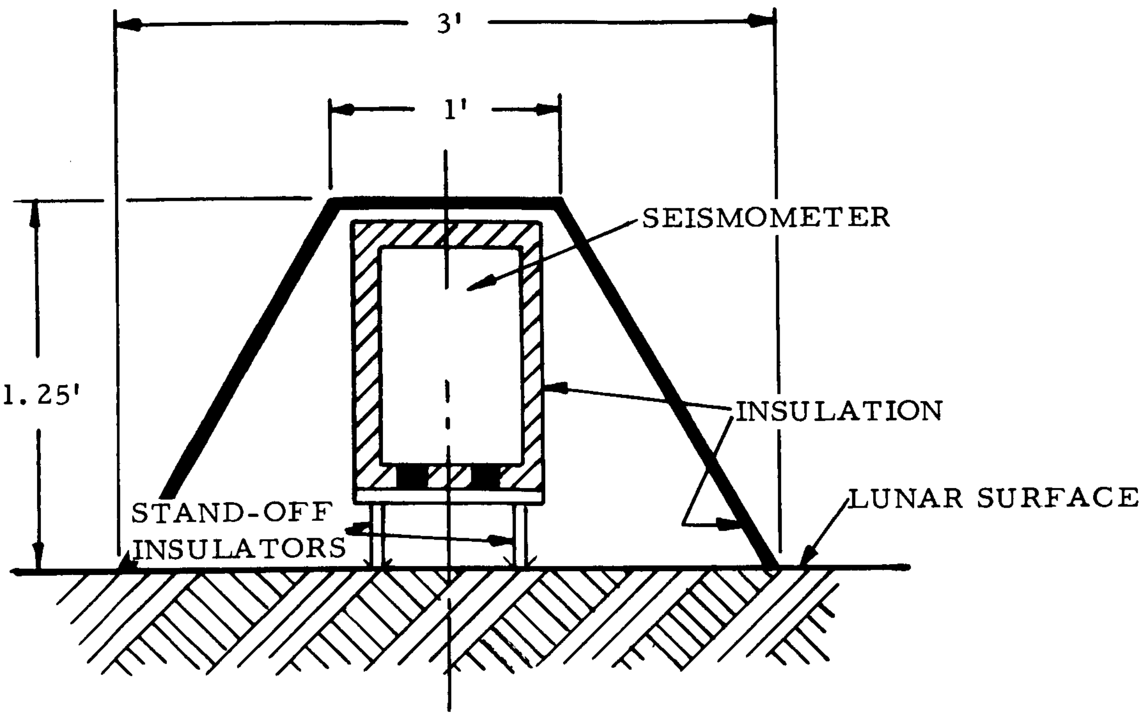

Figure V-8. Insulation Scheme for Combination Seismometer (after Lamont Geophysical Observatory, 1962)

be set up near the extreme end of the astronaut's traverse. It can be emplaced only if a traverse of the order of 500 ft is possible. This need to transport the SIP over such a distance presents some severe problems since the proposed SIP is both heavy and bulky.

Two methods have been suggested for handling the equipment and instruments during the traverse. The most obvious is a wheeled vehicle or cart which the astronaut could pull or push over the lunar surface. Difficulties with this approach are its probable greater cost in terms of weight (though the use of lightweight materials would reduce this penalty to a minimum) and the stability problems of a wheeled vehicle under conditions of lunar gravity which would force circumvention of possible surface protuberances, crevices and rilles (Miller, 1961). The vehicle would require the use of one or both hands, but this would tend to improve the astronaut's stability.

The other method would be the use of a lightweight shoulder yoke with the SIP instruments and equipment suspended on either side approximately a foot above the surface. This arrangement will lend stability to the astronaut by lowering his center of gravity, increasing his traction and balancing him. Also, it would free both hands so that he could use his staff for probing the surface ahead of him. A probable difficulty with the yoke is interference with the back-pack life support system and the pressure suit helmet. Also, it would require splitting the instrument and equipment load into two balanced packages.

b. Emplacement Requirements

Among the components of the SIP proposed for the first flight is a magnetometer. The sensor head of this device must be separated as far as possible from the rest of the package to protect its measured data from stray magnetic fields of other instruments. The required removal distance probably will be a minimum of 20 ft, depending on the design and shielding of the remainder of the package.

The only other instrument items which will require separation from the main part of the package are the platinum resistance surface temperature loop, thermal conductivity probe, micrometeoroid and ejecta detector, line source pressure gauge, and radiometric heat flow meter. The resistance thermometer loop must be carefully spread out on the surface and very carefully covered with a thin layer of dust (1 mm or less) if available. The probe must be inserted into a deeper dust layer if present, or into accessible cracks and crevices at the greatest depth possible. In the latter case, it will measure only subsurface temperature accurately, as good thermal contact with the surrounding material will be lacking.

If a radioisotope power source is used, it may be necessary to separate it from the other instrument packages to reduce the radiation flux density to which they are subjected. The necessity for this will depend critically on the shielding incorporated into the power supply and on the design of the instruments for resistance to damage by radiation. On the other hand, since the mission weight constraint is closely approached by the recommended instrumentation and equipment, separation of the radioisotope power supply can be assumed in order to reduce its weight by minimization of shielding requirements.

Any separation of the power supply from the other instrumentation introduces a thermal control problem on the connecting cabling. The large temperature extremes of the lunar surface could result in significant changes in cable resistance and, hence, a significant variation in the voltage available at the instruments, unless suitable thermal control measures are taken. This has been previously discussed but is repeated here, since one of the most effective thermal control measures would be to cover the cable with a layer of loose dust several cm thick. The possible absence of dust, however, and the time required of the astronaut to cover the cable necessitate consideration of other means of thermal control of the cabling. Cabling to separated instruments is not expected to be a problem since the cables will be carrying relatively small currents. In addition, the instruments can be designed in such a way that differences in the voltage drop in the cable will not affect results significantly.

The seismometer will be a part of the main package of the first flight and will not require separation. However, it must be suitably coupled to solid ground or rock when emplaced. Steps in its activation also will include coarse leveling and uncaging of the inertial masses. Fine leveling will be an automatic adjustment now built into the instrument. Other steps in emplacing and activating the main instrument package will be (1) setting up the antenna and orienting it toward the earth, (2) arranging any umbrellas or other measures determined to be necessary for thermal control and (3) activating the entire instrument for engineering checkout by earth control. The latter should be completed while the astronaut is still in the vicinity of the SIP so that he can take corrective measures if indicated.

5. Instrument Mode of Operation in the SIP

As discussed previously, certain of the measurements to be made by the SIP will be sequentially programmed to reduce the data acquisition rate to a level that can be handled adequately by the buffer storage units in the telemetry system. Only the long-period seismometers and the survey rate meter will operate continuously. The latter, together with the tidal gravity output of the combination seismometer, the helium magnetometer, the surface temperature loop and the thermal conductivity probe, will be programmed to yield data sequentially to reduce the peak data acquisition rate.

The short-period seismometer will be activated by command since measurement periods of varying times will be desired from this instrument. These must be obtained during times when earth-based instrumentation facilities are available for tracking throughout a run. All other instruments also should be capable of command turn-on. The helium magnetometer probably would be turned on for a lengthy run during a magnetic storm detected by geomagnetic observatories on earth. It also would be activated automatically when the survey rate meter detected an increase in incident ionizing radiation above some predetermined level.

Complete details of the various instrument operating modes, programming sequences and command operation capabilities and flexibility must await actual design of the SIP and its associated telemetry and control system and power supply.

F. CONCLUSIONS

Estimated payload requirements of the total recommended scientific instrumentation and equipment for Flight I, Alternative I, fall within the constraints provided by NASA Manned Spacecraft Center, with the use of either a battery pack/solar cell or a radioisotope power supply. The latter power supply, however, results in a package distribution that differs from the guidelines for volume allocation between the ascent and descent stages. Accordingly, use of the battery pack/solar cell power supply is recommended for Alternative I.

Estimated payload requirements for the recommended instrumentation and equipment for Alternative II fall within the constraints only with the use of the radioisotope power supply and the deletion of the gravity meter. The volume distribution problem is the same as for Alternative I. Since the constraints are not exceeded, the radioisotope power supply is recommended for Alternative II. However, the apparent volume distribution advantage accompanying the use of the battery pack/solar cell array and the fact that only the weight constraint was exceeded (and by only 6 per cent) suggest that final choice of power supply type await a detailed design study of the SIP.

Payload requirements estimated for the third flight are only 0.2 lb over the weight constraint. A battery pack/solar cell system will provide sufficient power to operate the instruments and telemetry system of the SIP package.

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CHAPTER VI

SYSTEMS ENGINEERING APPROACH

A. INTRODUCTION

The purpose of this chapter is to consider in detail the mechanics of a decision-making process used as an aid to select instrumentation for early APOLLO missions. All data, quantitative and qualitative, are identified and their integration discussed.

The considerations included in this study and discussed further below are:

- Definition of objectives and constraints
- System synthesis or postulation of feasible systems
- System analysis and evaluation
- Selection of the best system

The specific model employed in this study is discussed in detail in the following sections.

B. DISCUSSION OF PROBLEM AND APPROACH TO SOLUTION

A general statement of the problem is selecting a combination of the optimum instruments and scientific investigations for the first APOLLO missions. The "system" to be considered as a solution to the problem is the set of instruments and measurements that best accomplish mission objectives within mission constraints.

Figure VI-1 is a block diagram of the decision-making model used in this study. It should be noted that there are interrelations and feedback common to all of the functional blocks, shown by the double-headed arrows in Figure VI-1. Also, the entire process is a dynamic one, and a discussion of the results at one point in time can be considered as an instantaneous view of an activity in motion. This is so because the technological, economic, political, and social influences are direct inputs to each of the functional blocks in Figure VI-1 and are also dynamic processes. Hence, one objective to define the mechanics of the problem-solving model is to provide the capability to handle frequent changes in input data with minimum difficulty in generating corresponding new solutions.

The dashed lines in Figure VI-1 designate that portion of the process with which this chapter is primarily concerned. The definition of

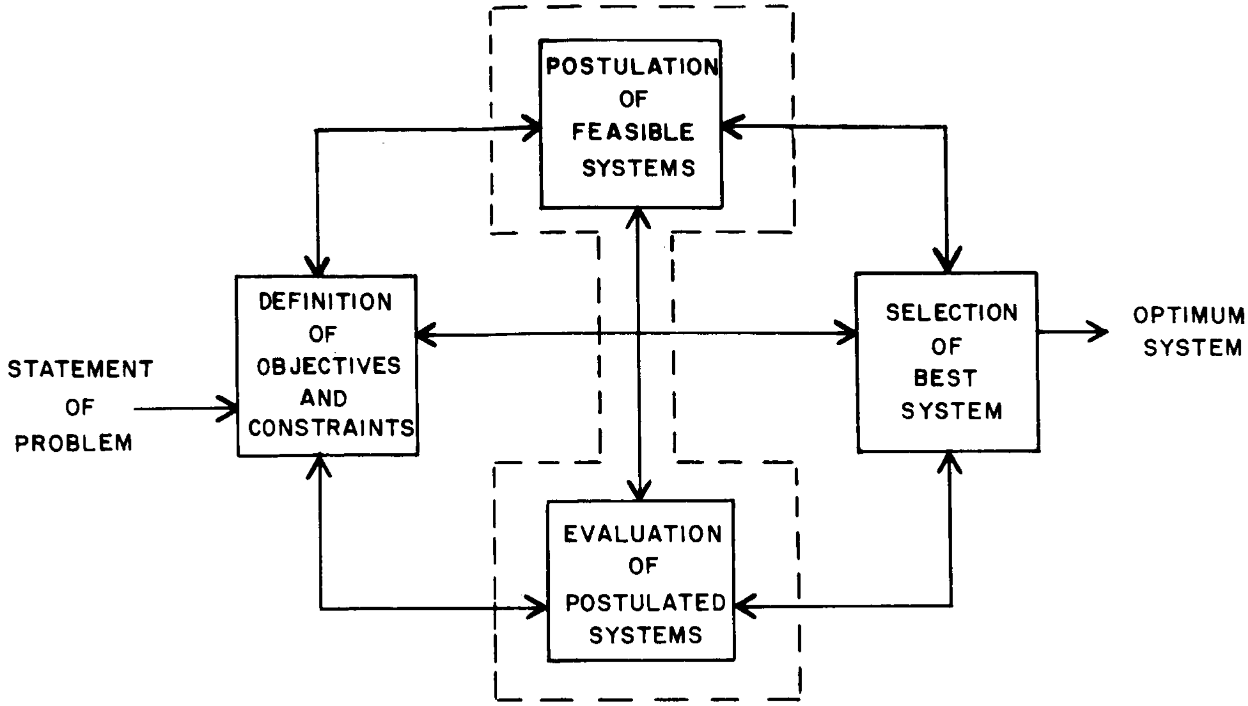

Figure VI-1. Decision-Making Model

problem objectives and constraints has been covered in Part I and will be reviewed only to the extent that it affects the mechanics of the decision-making process. Similarly, the final selection of a system design was discussed in a previous chapter. Only the interrelations and feedback from those functions will be discussed in this section.

1. Definition of Objectives and Constraints

The primary objectives of early APOLLO missions, in order of priority, are:

- To assure the safety of the astronauts on the round trip to, and their stay on, the moon
- To collect engineering data necessary for subsequent lunar landings
- To gather scientific knowledge about the moon and the earth-moon system

Scientific instrumentation selected for early missions must be compatible with the objectives of the overall mission, while being directed primarily toward maximizing the scientific returns within the allotted constraints. The emphasis placed on each of the listed objectives may change in time and the mechanics of the evaluation process permit coping with such changes in emphasis.

The power, weight, volume, and astronaut's time allocations for the first mission were set forth by NASA-MSC and are summarized in Table VI-1.

In establishing realistic constraints for the total power, weight, volume, and astronaut's time available for scientific investigations, special consideration was given to each of the allocations shown in Table VI-1.

TABLE VI-1

SCIENTIFIC INSTRUMENTATION ALLOCATIONS FOR FIRST MISSION

	Alternative I	Alternative II
Time	120 min	270 min
Weight	250 lb	250 lb
Volume	10 ft^3	10 ft^3
Power	750 w	750 w

The power specified in Table VI-1 was defined to be the maximum power that could be drawn from the LEM's primary power supply by the scientific instrumentation. Many of the instruments recommended for the early APOLLO missions are to be operated along the astronaut's traverse or at a remote location. The requirements for the portable power sources were converted into corresponding weight and volume requirements and included in the specifications shown in Appendix F.

A special consideration which tends to reduce the weight and volume available for scientific instrumentation is the telemetry system requirements for the SIP. Chapter V indicates the requirements of the telemetry system to be 48 lb and 1700 $in.^3$. The requirements for the telemetry power source are approximately 46 lb and 900 $in.^3$.

An allowance of roughly 20 per cent of total weight and volume allocations was made for packaging and thermal control. This allowance is considered a reasonable estimate, and the exact requirements can be specified after a detailed design study.

A further modification of problem constraints was due to subtracting from the totals the requirements for sampling and the sampling package selected for each alternative (see Chapter IV). The requirements are 10.7 lb, 250 $in.^3$ and 19 min for the first alternative and 12.8 lb, 323 $in.^3$ and 39 min for the second alternative.

The final requirement of the scientific investigation that is more or less independent of the specific choice of instrumentation is the time required for the astronaut to walk to and from sampling sites, SIP location and points of specific interest along his planned traverse. For the first alternative of the first flight, 15 min was allowed for nonassignable walking time (not including estimates for instrument setup time and visual observation). For the second alternative, a total of 45 min was allotted.

The effects of the allowances discussed above on the power, weight, volume, and time available for scientific investigation are summarized in Table VI-2. The values indicated in Table VI-2 were used as problem constraints in this study.

TABLE VI-2

EVALUATION PROGRAM CONSTRAINTS
FOR FIRST MISSION

	Alternative I	Alternative II
Time	86 min	186 min
Weight	103.3 lb	101.2 lb
Volume	11,500 in.^{3}	11,400 in.^{3}
Power	750 w	750 w

2. Postulation of Feasible Systems

The "system" considered in this study is the set of instruments to be used by the astronauts to make the observations and measurements. The "desired" or "ideal system" is that set of instruments and measurements which maximizes the technologic and scientific return from each mission. A "feasible system" is any set of instruments and measurements which falls within the specific mission constraints.

One logical way to generate a feasible system is to select a group of measurements and related apparatus from those discussed and recommended in the preceding chapters and to list as many of these as possible that collectively fall within the constraints of the mission. In attempting to compile a comprehensive set of such lists, it is soon recognized that a multitude of feasible sets could be selected. Further investigation shows that from the list of approximately 100 instruments and related measurements, the number of possible feasible systems is well in excess of 10^{30}, for all practical purposes an uncountable number.

The necessary feature in the above approach is the interconnecting feedback from the systems-evaluation to the systems-generation functional block as evidenced in Figure VI-1. Hence, in practice, one knows from a priori assumptions and learns from practical experience that most of the technically feasible systems do not merit consideration. Therefore, after a comprehensive survey of feasible systems, the most important can be compiled in a list from which, through further comparison and evaluation, the best system can be selected.

Two basic disadvantages with this process are: (1) the procedure is long and tedious and is completely altered by a change in either objectives or constraints; and (2) a priori assumptions and practical experience are not easily identifiable, and those used may not be representative of the scientific community as a whole. The latter is especially important in a program as interdisciplinary in nature as APOLLO.

If a group of specialists representing each of the various pertinent scientific disciplines collectively postulates and evaluates the feasible systems, the results of the generation-evaluation procedure are greatly improved. This, in fact, is the approach used in the present program. The disadvantages are: (1) the a priori assumptions and practical experience of the group, even though they are representative of the scientific community, are difficult to identify and record; and (2) as before, the "system-synthesis-system-analysis" loop is a tedious and time consuming process subject to major alterations resulting from changes in the objectives or constraints of the problem.

The approach to be presented in the remainder of this chapter is an attempt to approximate quantitatively the generation-evaluation processes of these specialists in a manner amenable to computer programming. The results will not be to replace the decision-making processes of the group in the generation-evaluation loop; instead, they will supplement and simplify the laborious task of considering the multitude of feasible instrument sets. The details are discussed in the following sections.

3. Evaluation of Possible Systems

The most difficult portion of the decision-making process, so far as the mechanics are concerned, is the systems analysis and evaluation. Exact interpretations of the problem objectives are needed to perform this function as well as appropriate units of value with which to evaluate the postulated systems.

There is considerable debate as to the correct interpretation of the objectives or the proper yardsticks to use as measuring devices. Therefore, evaluation of a system by an individual probably will not be representative of the scientific community as a whole. As stated previously, a group of highly specialized individuals representing pertinent scientific disciplines improves the evaluation substantially. The "computer evaluation" technique evolved from an attempt to identify and record the individuals' and groups' value interpretations. The technique takes into account the inherent subjectivity in the decision-making mechanism.

The evaluation by individuals and the group was divided into five relatively independent areas of interest. These are referred to as "problem areas" and are identified as: (1) hazards to the astronauts; (2) trafficability; (3) lunar basing; (4) lunar surface age, history or origin; and (5) earth-moon system age, history or origin. These five problem areas can be directly correlated with the APOLLO mission objectives. The relevance and importance of a given measurement within each problem area was selected as a measure of value for that measurement.

Each measurement discussed in Chapters II-IV and included in Appendix E was placed in one of the following five categories for each problem area:

I Irrelevant to this problem area

II Possibly contributes to this problem area but not in a known, direct manner

III Contributes directly to this problem area but not considered important

IV Contributes directly to this problem area and considered important but not an essential measurement

V Considered important to this problem area and classified essential

This classification for each measurement was done by the respective study groups to achieve a basis of comparison for the many possible measurements and related instruments for each mission.

A single instrument or set of instruments often will perform several measurements; e.g., hand camera, staff, hand lens, etc., to name a few. Therefore, the list of measurements shown in Appendix E was rearranged so that all of the measurements that could be performed by one or a group of instruments were listed as a subgroup. Consequently, several measurements from a subgroup could be considered in the same system at no greater cost, in terms of instrumentation, than a single member of that group. The cost for additional members of a subgroup would increase, however, in terms of the time required to make each additional measurement. The value of the set would correspondingly increase by the value assigned to each additional measurement. This inverted form of the data matrix is shown in Appendix F. Also included in Appendix F are the computer program inputs which are discussed in detail in Appendix G.

The most difficult part of the entire operation is to establish a realistic measuring scale to evaluate the many possible systems. Even more basic is the difficulty in establishing a measure of value for a single parameter measurement. Studies of economic and psychological theories of value (Hall, 1962) show that, to perform mathematical operations such as addition or multiplication, the measuring scale must have the properties of a "ratio scale". The key properties of a ratio scale are the following:

- The zero of the scale is "natural", or absolute.

- The ratio of one measurement to another is unchanged by a scale change such as $y = cx$ where c is a nonzero constant.

Thus, to determine the "value" of a set of measurements by adding the value of each member of the set, value scales must be made to approximate a ratio scale. This was accomplished by noting that Category I is a natural zero for a "value" scale; i.e., an irrelevant measurement contributes nothing and hence has zero "value". The choice of a unit of measure is completely arbitrary for a ratio scale, thus Category II was chosen to have a "value" of 1. The values assigned to Categories III, IV and V were empirically determined as ratios to the arbitrary value of Category II. Since the computer evaluation program was designed to supplement the postulation-evaluation loop of the group of specialists, the ratios for Categories III, IV and V were adjusted to reflect the a priori assumptions and practical experience of the group. The ratios selected during this study are 3, 10 and 20, respectively. The literal interpretation of these values is that the importance of Categories III, IV and V is 3, 10 and 20 times the value of Category II.

A shift in emphasis on the problem objectives is noted for each mission; e.g., hazard measurements are more important during initial missions. Such shifts in emphasis directly affect the evaluation of each measurement and hence each system. This was incorporated into the evaluation scheme by weighting each problem area by an appropriate weighting factor C_k. Figure VI-2 exemplifies this process, wherein measurement M is evaluated in terms of each problem area and classified in Categories I, II, III, IV, or V. The corresponding value of each is then multiplied by the appropriate weighting factor and summed to give the "value" or "scientific figure-of-merit", S(M) for measurement M.

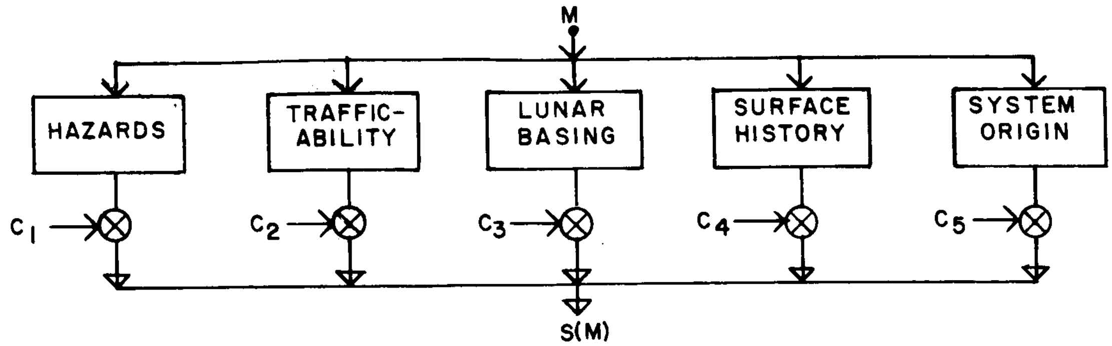

Figure VI-2. Flow Chart for Determining Scientific Figure-of-Merit

The weighting factors were empirically determined to represent the desired emphasis on each of the five problem areas for various missions. The values resulting from this study are discussed subsequently.

Once the values S(M) have been determined for all measurements, the value of a system consisting of a specified combination of measurements can be determined by summing the corresponding measurements' figures-of-merit. In this manner, an evaluation scheme was established that reflects the study groups' ratings of the measurements and that can be handled in a computer program. The evaluation is unavoidably inexact, however, primarily for the following reasons:

- Five broadly defined problem areas have been used as bases for evaluation, but there is a vast number of additional problem objectives (economic, social, political, etc.) which also could be used as bases.

- The classification of a given measurement within each problem area is subjective and, therefore, subject to individual interpretation of the problem objectives.

- The number of categories of classification was limited to five, and thus the resolution of the importance of a measurement is similarly limited.

- The interrelations among the measurements and instruments within a system have not been considered. Thus, the possibility of "the whole being greater than the sum of its parts" is not considered in the computer program.

The effect of the imperfections in the evaluation process is to generate several systems, or sets of measurements, which the evaluation cannot confidently resolve. In other words, the uncertainty in the input values is propagated throughout the process and the results are interpreted as reflecting that uncertainty.

The computer evaluation program was designed to generate 100 systems with the highest total scientific figures-of-merit. The 100 sets of measurements were then re-evaluated by the group and the best system chosen. This choice was made by comparing the requirements and consequences of each system in view of the overall interpretation of all the problem objectives and constraints. The systems selected for early APOLLO missions were discussed in Chapter II of Part I.

C. RESULTS

The computer evaluation program was designed to facilitate the task of postulating and evaluating many possible combinations of measurements and instruments for each set of problem objectives and constraints. The program accepts the input data shown in Appendix F and generates the 100 combinations of measurements and instruments that have the highest total scientific figures-of-merit for the specified objectives and constraints. The inherent inexactness in specifying quantitatively the mission objectives and measurement values results in the top ranking 100 combinations being a degenerate set of solutions; i.e., the uncertainty in the evaluation is such that the total scientific figures-of-merit for the various systems cannot be resolved.

The results of the computer evaluation reveal that the top ranking 100 combinations of measurements are very similar. In fact, of the approximately 30 measurements included in each set, roughly one-half are common to all of the top ranking combinations. Also, any two combinations in the top ranking 100 differ by, at most, five measurements. The consequence of the computer program is a compilation of approximately 50 measurements which appear in various combinations in the top ranking 100 sets of measurements. Hence, the total number of times each measurement was included in the top ranking 100 provides a useful summary of the evaluation results. Examples of the summarized outputs are shown on the following pages. A more detailed discussion of the evaluation program results is included in Appendix G.

During the study, several numerical values were used for the measurement rating "values" for Categories III, IV and V. It was found that the results were affected very little by changes in these numerical ratings within a fairly wide range of values. The values used in the results shown below are $R_{III} = 3$, $R_{IV} = 10$ and $R_V = 20$, as previously discussed.

Also, several numerical values for the five weighting factors were used as inputs to the computer, reflecting different emphasis on the safety, technologic or scientific aspects of the mission. A change in the relative emphasis of any of the five problem areas is reflected in the results.

In the sample results shown, TIMES INCLUDED means the total number of times the specified measurement was included in the 100 combinations with the highest total scientific figures-of-merit. INSTRUMENT refers to the computer's name for the specified instrument/measurement(s). Under the heading INSTRUMENT (MEASUREMENTS) are listed the instruments used to perform the measurements indicated in parentheses. In some cases where several measurements were to be specified, the index numbers of the measurements from Appendix F were indicated rather than an abbreviated form of the several measurements.

Examples of the effects of a shift in emphasis on specific mission objectives are shown in the sample results on the following pages. The numerical values of the weighting factors for each problem area rating for the four cases shown are summarized in Table VI-3.

TABLE VI-3

WEIGHTING FACTORS FOR SAMPLE CASES

Mission	Case	Weighting Factors				
		Hazards	Traffic	L.B.	L.S.	E-M SYS
Alternative I	1	6.0	1.5	1.5	0.5	0.5
	2	1.0	1.5	1.5	3.0	3.0
Alternative II	1	6.0	1.5	1.5	0.5	0.5
	2	1.0	1.5	1.5	3.0	3.0

Results of the computer evaluation program, such as those shown on the following pages, are especially useful in evaluating the effects on the optimum instrumentation of any of the following:

- A change in the power, weight, volume, or astronaut's time allotted for scientific investigations on the first APOLLO mission
- Development or improvement of an instrument design for any of the measurements considered in the evaluation program
- Successful measurement or observation by an unmanned lunar mission which may change the desirability or scientific figure-of-merit of any of the parameter measurements included in the evaluation program

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. I

6.1.5.1.5..5'.5

TIMES INCLUDED	INSTRUMENT*	INSTRUMENTS(MEASUREMENTS)
100	130	PERS INTEG DOSIMET(CUM RAD DOSE)
100	126	SURVEY RATE METER(36CD)
99	152	VO(ELECTROSTATICS)
100	165	PLAT RESIST BRIDGE(LAND GEAR T)
100	184	JS(81AB)
100	210	VO (EROSION)
96	209	INCL(ANGLE OF REPOSE)
1	153	CHARGED DUST DET(ELECTROSTATICS)
99	166	THERMO COUPLE (BOOT TEMP)
4	208	VO(ANGLE OF REPOSE)
100	179	LEM TV TRACKER(76ABC)
100	207	VO(TRANSPORTATION)
100	89	VO MAPS HC(OCCURENCE STEEP SLOPE
99	122	SAMP CULT PH RO(DET LIFE FORMS)
92	211	VO (RADIATION DAMAGE)
86	80	VO SP (ABRASIVE HARDNESS)
92	212	VO (MICROMETEORITE ACCRETION)
96	191	JS/PENETROMETER(PENETRAT RESIST)
95	197	TETHER SPHERE(PENETRAT RESIST)
87	4	VO MAPS (DEPOSITION)
100	88	DESCENT CAMERA (17ABCD)
92	203	VO (SINTERING)
99	178	HC LEM TARGET(75AB)
1	5	VO MAPS (3AB)
98	193	HC SP-LENS(BEARING STRENGTH)
97	129	CHEM REACTIVITY DET(CHEM REACT)
83	202	VO (EFFECTS THERMAL CYCLING)
82	205	VO (VAC. OUTGAS.)
8	3	VO MAPS (X SECT TOPO)
1	195	HC SP-LENS (88AB)
90	125	SURVEY RATE METER(36AB)
1	176	HC LEM TARGET(SS +SIP DISTANCE)
4	87	VO MAPS INCL (SLOPE)
100	127	PARTICLE SPEC(37AB)
17	196	SAMPLING PACK.(SOIL DENSITY)
15	169	THERM PROBE(LAND GEAR THER COND)
2	1	VO HL JS (DUST TEXT,CONSIS,COMP)
1	194	HC SP-LENS (STRAT.ELEM. OF SOIL)
32	82	GYRO INCL(A3 TO SAMP SITE + SIP)
9	71	VO HL ST(ORE MINER KIND + AMT)
1	123	SAMP CULT RADIOISO RO(LIFE FORM)
6	216	VO (SOIL COLOR)
11	155	GM (GRAVITY)
15	124	SOLAR PLAS SPEC (35AB)
7	156	GRADIOMETER(GRAVITY GRADIENT)
7	137	TI HM(VER HOR VECT SUM DIR MAGF)

* Computer name for instrument/measurement(s).

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. I

1.,1.5,1.5,3.,3.

TIMES INCLUDED	INSTRUMENT *	INSTRUMENTS(MEASUREMENTS)
100	130	PERS INTEG DOSIMET(CUM RAD DOSE)
100	126	SURVEY RATE METER(36CD)
100	210	VO (EROSION)
100	212	VO (MICROMETEORITE ACCRETION)
100	209	INCL(ANGLE OF REPOSE)
98	211	VO (RADIATION DAMAGE)
97	152	VO(ELECTROSTATICS)
100	179	LEM TV TRACKER(76ABC)
97	203	VO (SINTERING)
100	178	HC LEM TARGET(75AB)
95	165	PLAT RESIST BRIDGE(LAND GEAR T)
93	205	VO (VAC, OUTGAS,)
100	88	DESCENT CAMERA (17ABCD)
90	202	VO (EFFECTS THERMAL CYCLING)
90	184	JS(81AB)
3	153	CHARGED DUST DET(ELECTROSTATICS)
92	4	VO MAPS (DEPOSITION)
86	207	VO(TRANSPORTATION)
3	5	VO MAPS (3AB)
96	71	VO HL ST(ORE MINER KIND + AMT)
10	182	JS(SOIL DEPTH + DUST THICKNESS)
3	3	VO MAPS (X SECT TOPO)
3	72	VO HL ST(7AB)
93	191	JS/PENETROMETER(PENETRAT RESIST)
86	80	VO SP (ABRASIVE HARDNESS)
87	166	THERMO COUPLE (BOOT TEMP)
95	89	VO MAPS HC(OCCURENCE STEEP SLOPE
83	168	THERM PROBE(66ABC)
41	196	SAMPLING PACK,(SOIL DENSITY)
32	195	HC SP-LENS (88AB)
66	194	HC SP-LENS (STRAT.ELEM. OF SOIL)
17	213	VO (LOCAL ORE + ITS GENESIS)
62	82	GYRO INCL(A3 TO SAMP SITE + SIP)
14	169	THERM PROBE(LAND GEAR THER COND)
24	155	GM (GRAVITY)
7	137	TI HM(VER HOR VECT SUM DIR MAGF)
1	193	HC SP-LENS(BEARING STRENGTH)
35	127	PARTICLE SPEC(37AB)
3	156	GRADIOMETER(GRAVITY GRADIENT)
9	124	SOLAR PLAS SPEC (35AB)
6	197	TETHER SPHERE(PENETRAT RESIST)

*Computer name or instrument/measurement(s).

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. II

6.1.5.1.5..5'..5

TIMES INCLUDED	INSTRUMENT*	INSTRUMENTS(MEASUREMENTS)
100	130	PERS INTEG DOSIMET(CUM RAD DOSE)
96	152	VO(ELECTROSTATICS)
100	210	VO (EROSION)
100	165	PLAT RESIST BRIDGE(LAND GEAR T)
100	126	SURVEY RATE METER(36CD)
100	184	JS(81AB)
100	209	INCL(ANGLE OF REPOSE)
100	166	THERMO COUPLE (BOOT TEMP)
99	207	VO(TRANSPORTATION)
4	153	CHARGED DUST DET(ELECTROSTATICS)
100	211	VO (RADIATION DAMAGE)
100	80	VO SP (ABRASIVE HARDNESS)
100	212	VO (MICROMETEORITE ACCRETION)
100	122	SAMP CULT PH RO(DET LIFE FORMS)
99	203	VO (SINTERING)
88	4	VO MAPS (DEPOSITION)
12	5	VO MAPS (3AB)
99	202	VO (EFFECTS THERMAL CYCLING)
100	89	VO MAPS HC(OCCURENCE STEEP SLOPE
99	129	CHEM REACTIVITY DET(CHEM REACT)
100	205	VO (VAC. OUTGAS.)
100	191	JS/PENETROMETER(PENETRAT RESIST)
100	179	LEM TV TRACKER(76ABC)
100	197	TETHER SPHERE(PENETRAT RESIST)
99	87	VO MAPS INCL (SLOPE)
100	178	HC LEM TARGET(75AB)
99	125	SURVEY RATE METER(36AB)
96	195	HC SP-LENS (88AB)
4	193	HC SP-LENS(BEARING STRENGTH)
1	206	EPMS(TRANSPORTATION)
100	88	DESCENT CAMERA (17ABCD)
81	196	SAMPLING PACK.(SOIL DENSITY)
75	168	THERM PROBE(66ABC)
74	128	PORT SURVEY RATE MET(38AB)
70	169	THERM PROBE(LAND GEAR THER COND)
81	1	VO HL JS (DUST TEXT,CONSIS,COMP)
90	127	PARTICLE SPEC(37AB)
68	167	PLAT RESIST LOOP(SURFACE TEMP)
69	71	VO HL ST(ORE MINER KIND + AMT)
27	72	VO HL ST(7AB)
67	73	HL (ROCK TEX GR SIZE/SHAPE PRO
62	82	GYRO INCL(A3 TO SAMP SITE + SIP)
55	116	GAMMA RAY SPEC(29ABCD)
2	70	VO HL ST(ROCK PETROGRAPHY)
68	213	VO (LOCAL ORE + ITS GENESIS)
19	174	REFLECT RADIOM(73ABC)
78	6	VO JS DES CAM (DUST-HORIZ,VERT)
10	133	MM + EJECTA DET(43AB)
3	74	HL (ROCK FAB GR ARR DIST)
9	216	VO (SOIL COLOR)
3	215	VO(ROCK COLOR)
18	155	GM (GRAVITY)
25	124	SOLAR PLAS SPEC (35AB)
10	156	GRADIOMETER(GRAVITY GRADIENT)
1	83	GYRO (INCL ORIENT ROCK SAMP)
8	137	TI HM(VER HOR VECT SUM DIR MAGF)

*Computer name for instrument/measurement(s).

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. II

1.,1.5,1.5,3.,3.

TIMES INCLUDED	INSTRUMENT *	INSTRUMENTS(MEASUREMENTS)
99	130	PERS INTEG DOSIMET(CUM RAD DOSE)
100	210	VO (EROSION)
100	212	VO (MICROMETEORITE ACCRETION)
100	126	SURVEY RATE METER(36CD)
100	211	VO (RADIATION DAMAGE)
92	152	VO(ELECTROSTATICS)
100	203	VO (SINTERING)
100	209	INCL(ANGLE OF REPOSE)
99	165	PLAT RESIST BRIDGE(LAND GEAR T)
100	205	VO (VAC. OUTGAS,)
100	178	HC LEM TARGET(75AB)
99	202	VO (EFFECTS THERMAL CYCLING)
98	207	VO(TRANSPORTATION)
99	5	VO MAPS (3AB)
1	4	VO MAPS (DEPOSITION)
75	71	VO HL ST(ORE MINER KIND + AMT)
98	184	JS(81AB)
25	72	VO HL ST(7AB)
96	80	VO SP (ABRASIVE HARDNESS)
100	179	LEM TV TRACKER(76ABC)
8	153	CHARGED DUST DET(ELECTROSTATICS)
100	168	THERM PROBE(66ABC)
99	196	SAMPLING PACK.(SOIL DENSITY)
96	166	THERMO COUPLE (BOOT TEMP)
2	182	JS(SOIL DEPTH + DUST THICKNESS)
98	213	VO (LOCAL ORE + ITS GENESIS)
99	191	JS/PENETROMETER(PENETRAT RESIST)
98	169	THERM PROBE(LAND GEAR THER COND)
97	87	VO MAPS INCL (SLOPE)
100	89	VO MAPS HC(OCCURENCE STEEP SLOPE
100	88	DESCENT CAMERA (17ABCD)
88	76	HL (8AB)
79	195	HC SP-LENS (88AB)
2	206	FPMS(TRANSPORTATION)
12	73	HL (ROCK TEX GR SIZE/SHAPE PRO
56	84	GYRO (11AB)
44	82	GYRO INCL(A3 TO SAMP SITE + SIP)
21	194	HC SP-LENS (STRAT.ELEM. OF SOIL)
48	216	VO (SOIL COLOR)
33	214	VO SP(MINERAL IDENT)
29	1	VO HL JS (DUST TEXT,CONSIS,COMP)
19	129	CHEM REACTIVITY DET(CHEM REACT)
77	167	PLAT RESIST LOOP(SURFACE TEMP)
70	215	VO(ROCK COLOR)
34	26	VO MAPS JS GYRO HC(6DF)
94	155	GM (GRAVITY)
31	125	SURVEY RATE METER(36AB)
12	122	SAMP CULT PH RO(DET LIFE FORMS)
9	137	TI HM(VER HOR VECT SUM DIR MAGF)
3	156	GRADIOMETER(GRAVITY GRADIENT)
70	127	PARTICLE SPEC(37AB)
12	124	SOLAR PLAS SPEC (35AB)
22	197	TETHER SPHERE(PENETRAT RESIST)

* Computer name for instrument/measurement(s).

D. CITED REFERENCE

Hall, Arthur D., 1962, A methodology for systems engineering: D. Van Nostrand Co., Inc., Princeton, N. J., 478 p.

APPENDIX A

REPLIES TO INQUIRIES CONCERNING THE MOST IMPORTANT MEASUREMENTS AND EXPERIMENTS TO BE MADE ON EARLY APOLLO MISSIONS

Inquiries, similar to the letter included as Figure A-1, were sent to the 50 scientists listed alphabetically in Table I. Twenty-two replies were received and summarized in terms of recommended early mission activities. Copies of replies are included in this appendix. These data are for the internal use of the National Aeronautics and Space Administration, and any reference to or publication of this material without the written permission of the individual involved is prohibited.

Recommended activities were rated according to the stated or implied priority assigned by the various respondents. Activities most frequently mentioned as high-priority items for early APOLLO missions were hazard analysis, sampling, photography, geologic studies, geophysical surveys, and passive monitoring of geophysical phenomena. The activity assigned the highest priority by each respondent was given a value of 4; second highest priority, 3; third highest, 2; and fourth, 1. All values for each activity were summed to obtain a total response value for each. This value was divided by the number of respondents mentioning the specific activity to obtain an average priority number for the activity. These data are summarized below:

	Total Response Value	Average Priority
Hazard Analysis	19	3.8
Sampling	33	3.3
Photography	15	2.5
Geologic Studies	12	2.4
Geophysical Surveys	9	2.3
Passive Monitoring	6	1.5

Hazard analysis had the highest average priority rating, but sampling was mentioned most frequently in the replies. Most respondents used such terms as "intelligent", "identification", or "planned" in conjunction with sampling. This indicates a strong preference for geological control of sampling and undoubtedly explains why geologic activities per se apparently received less emphasis and a lower rating. Although the replies represent a very small sampling of the scientific community, there is general agreement on the fact that hazard analysis, sampling and photography should be emphasized on early APOLLO missions.

TABLE I

ALPHABETICAL LIST OF SCIENTISTS CONTACTED

Dr. Philip Abelson
Editor, Science
1515 Massachusetts Ave.
Washington 5, D. C.

*Dr. Ralph Baldwin
1745 Alexander Rd. S.E.
East Grand Rapids, Michigan

Dr. M. G. Bekker
General Motors Research Lab
Goleta, California

*Dr. Lloyd Berkner, President
Graduate Research Center of
the Southwest
P. O. Box 8478
Dallas 5, Texas
cc: Dr. Frank Johnson
Dr. Anton Hales

Dr. Harrison S. Brown
Division of Geological Sciences
California Institute of Technology
Pasadena, California

*Dr. A. G. W. Cameron
Institute for Space Studies
475 Riverside Drive
New York 27, New York

*Mr. Robert Carder
Aeronautical Charting and
Information Center
United States Air Force
St. Louis 18, Missouri

*Dr. A. J. Dessler
Department of Space Studies
Rice University
Houston, Texas
cc: Dr. King Walters
Physics Department

Dr. G. de Vaucouleurs
Department of Astronomy
University of Texas
Austin, Texas

*Dr. Maurice Ewing
Lamont Geological Observatory
Columbia University
New York, New York

*Dr. Gilbert Fielder
University of London Observatory
Mill Hill Park
London N. W. 7, England

*Dr. Thomas Gold
Director, Center for Radiophysics
and Space Research
Phillips Hall
Cornell University
Ithaca, New York
cc: Dr. Bruce Hapke

*Dr. Jack Green
Space and Information Systems
North American Aviation
12214 Lakewood Blvd.
Downey, California

*Mr. Bruce Hall
Code ENGMC-ED
Technical Development Branch
Office, Chief of Engineers
Gravelly Point
Washington 25, D. C.

*Dr. Harry H. Hess
Department of Geology
Princeton University
Princeton, New Jersey

*Written or verbal response received to letter of inquiry.

*Dr. Robert E. Jastrow
Institute for Space Studies
475 Riverside Drive
New York 27, New York

*Dr. William W. Kellogg
Head, Planetary Sciences
The Rand Corporation
1700 Main Street
Santa Monica, California

*Dr. Zdenek Kopal
Department of Astronomy
The University of Manchester
Manchester 13, England

*Dr. Robert L. Kovach
Research Fellow
California Institute of Technology
Seismological Laboratory
Pasadena, California

*Dr. Gerard P. Kuiper
Director
Lunar and Planetary Laboratory
The University of Arizona
Tucson, Arizona

*Dr. Benjamin B. Lane, Jr.
Acting Technical Director
Headquarters, Aeronautical Chart
& Information Center
United States Air Force
Second and Arsenal
St. Louis, Missouri

Dr. Joshua Lederberg
Department of Genetics
School of Medicine
Stanford University
Palo Alto, California

Dr. Alden Albert Loomis
Lunar and Planetary Science Section
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California

*Dr. Paul D. Lowman, Jr.
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. Gordon J. F. McDonald
Institute of Geophysics and
Planetary Physics
University of California
Los Angeles 24, California

*Dr. Hugh Odishaw
Executive Director
Space Science Board
National Academy of Sciences
2101 Constitution Avenue
Washington 25, D. C.

*Dr. John O'Keefe
Assistant Chief
Theoretical Division
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. E. J. Öpik
Astronomical Observatory
Armagh, Northern Ireland

*Dr. Frank Press
Seismological Lab
California Institute of Technology
Pasadena, California

*Dr. Carl Sagan
Director
Astrophysical Observatory
Smithsonian Institution
60 Garden Street
Cambridge 38, Massachusetts

Dr. J. W. Salisbury
Air Force Cambridge Research
Laboratories
Laurence G. Hanscom Field
Bedford, Massachusetts

Dr. Ronald F. Scott
Department of Civil Engineering
California Institute of Technology
Pasadena, California

*Written or verbal response received to letter of inquiry.

Dr. Eugene Shoemaker
Astrogeology Branch
U. S. Geological Survey
Flagstaff, Arizona
cc: Dr. Verne Frykland

*Dr. S. F. Singer
Professor of Physics and Director
Center for Atmospheric and Space Physics
University of Maryland
College Park, Maryland

Dr. William M. Sinton
Lowell Observatory
Flagstaff, Arizona

Dr. Charles P. Sonett
Ames Research Center
Moffett Field, California

*Dr. Robert C. Speed
Lunar and Planetary Science Section
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California

Dr. Lyman Spitzer
Director, Princeton University Observatory
Princeton, New Jersey

*Dr. Harold C. Urey
School of Science and Engineering
University of California at San Diego
La Jolla, California

Dr. James A. Van Allen
Head, Department of Physics and Astronomy
State University of Iowa
Iowa City, Iowa

Dr. H. C. van de Hulst
Leiden Observatory
Leiden, Holland

*Dr. Wernher Von Braun
Director, NASA Marshall Space Flight Center
Huntsville, Alabama

*Dr. Louis S. Walter
NASA
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. J. Tuzo Wilson
Chairman, Department of Geophysics
University of Toronto
Toronto, Canada

*Dr. George P. Woollard
Head, Geophysics Institute
University of Hawaii
Honolulu, Hawaii

*Written or verbal response received to letter of inquiry.

TEXAS INSTRUMENTS
INCORPORATED
100 EXCHANGE PARK NORTH • DALLAS, TEXAS
SCIENCE SERVICES DIVISION

Dear ____________:

NASA's Manned Spacecraft Center has asked us to study the problem of determining optimum measurements, experiments and geologic-geophysical studies to be made on the lunar surface during the APOLLO program. One of the early requirements of this study is to obtain and compile pertinent thoughts of prominent space and lunar scientists. We are familiar with most of your publications in this field, testimonies presented at congressional hearings, and the reports of previous NASA study groups concerned with certain aspects of the problem under consideration. We would, however, greatly appreciate receiving new information or ideas you might have and/or references to specific publications that most closely duplicate your current views.

The opinions you and your associates may have concerning the most important types of data to be obtained and the manner in which they are to be measured -- including pertinent instruments and procedures -- are of primary interest. Because of stringent limitations on observation time and equipment weight, particularly during early lunar missions, suggestions as to the priority for various types of measurements are also of major concern. Criteria to determine priority include the degree to which the measurement would help assure the safety of the astronaut, improve the efficiency of future missions and aid in the solution of problems concerning the origin of the moon, earth and solar system.

The study is subject to a rigid time schedule and it is necessary to request receipt of comments or suggestions at your earliest convenience. All data will receive very careful consideration in the study and your cooperation will be most helpful and greatly appreciated.

Sincerely,

Jack R. Van Lopik

Richard A. Geyer

Technical Directors
APOLLO Study

MAILING ADDRESS: POST OFFICE BOX 35084 • DALLAS, TEXAS • FLEETWOOD 7-4311 • CABLE: TEXINS

SAMPLE LETTER OF INQUIRY

OLIVER
MACHINERY COMPANY
GLENDALE 6-1592
GRAND RAPIDS 2, MICHIGAN, U.S.A.

November 6, 1963

Mr. Jack R. Van Lopik
Mr. Richard A. Geyer
Technical Directors
Apollo Study
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Gentlemen:

Your request for help on certain phases of studies on the lunar surface is a difficult one to answer.

My new book The Measure of the Moon summarizes many of the opinions which I now hold. In addition, there has been a considerable amount of new work and new interpretations made concerning the lunar surface within the last year. I am in process of preparing several papers on this subject, which have not yet gone to press, and have developed some very specific ideas concerning the lunar surface and some measures and tests which need to be made. However, I do not think that this can be properly done by letter. If you would care to establish a consultant's arrangement, it is possible I could come to Dallas; or, even better, one of your men could come to Grand Rapids for a discussion.

It is not through any reluctance to cooperate that I make this suggestion but only that I feel it cannot be limited to impersonal correspondence.

Sincerely yours,

Ralph B. Baldwin

Ralph B. Baldwin

RBBpj

GRADUATE RESEARCH CENTER

OF THE SOUTHWEST
POST OFFICE BOX 8478
DALLAS 5, TEXAS

OFFICE OF THE PRESIDENT | EMERSON 3-5211 | CABLES· GRADRESCEN

November 20, 1963

Dr. Jack R. Van Lopik
Dr. Richard A. Geyer
Technical Directors, Apollo Study
Texas Instruments Incorporated
100 Exchange Park North
Dallas, Texas

Dear Dr. Van Lopik and Dr. Geyer:

I am replying to your letter of October 25, 1963 which requests my views on the optimum measurements, experiments and geological-geophysical studies to be made on the lunar surface during the Apollo program. These are matters to which I have given considerable thought and attention, although at the same time I have not had occasion to examine details of the instrumentation and equipment which might be required for such scientific studies. I should like, therefore, to offer my views in a broad sense and to then make some suggestions which may help you in gathering more details.

First of all, most scientists recognize that the Apollo Program is and will continue to be fundamentally a great engineering effort and that engineering decisions necessary to the successful accomplishment of the mission and the safe return of astronauts must take overriding priority over all other considerations. Consequently, the scientific community looks upon the scientific opportunities to investigate the Moon as more likely to be achieved in depth only in succeeding stages of the manned space flight program after Apollo has been accomplished.

Therefore, in terms of the most urgent science which should be undertaken in the Apollo mission, scientists agree that the first scientific investigations must be directed toward studies of, for example, the nature and characteristics of the lunar surface (including such parameters as the possibilities of electrostatic dust hazards or extreme surface friability), the range and extent of temperature extremes at the lunar surface, meteoritic activity, surface radiation exposures, and so on. In terms of safety for the Apollo mission, such studies must be given the highest priority. However, it is vital to remember that a vast amount of additional information can and will be achieved prior to the first lunar landing: maximum advantage of all scientific means and techniques to extend our information by ground-based observations on these environmental characteristics should be undertaken. I should add also that the current plan for a lunar orbiting satellite from which a manned capsule will be sent to the lunar surface requires the most precise information possible about the lunar gravitational field and lunar geodetic effects. Here, while science will benefit greatly in fundamental knowledge, information about these parameters may be critical to the successful lunar landing operation.

Presuming a successful manned lunar landing, the nature of the first and most important experiments which can be undertaken will then be governed by a number of other factors, many of which are still undetermined, insofar as I know, at the present time. In this connection, I refer particularly to such considerations as the time available on the lunar surface and the total weight of scientific instrumentation which may be carried. For example, if it is decided that the first Apollo missions can spend only a few minutes (or an hour or two on the lunar surface), I believe the considerations as to the science that should be undertaken are considerably different than if a day or longer is possible. Weight limitations would apply similar constraints; for example, if it is possible to carry only 100 lbs. of scientific equipment the research investigations would differ enormously from those in which perhaps 1,000 lbs. could be transported. Consequently specification of these parameters seems absolutely essential to an intelligent response to your present letter and to the analyses which you are undertaking for the Manned Spacecraft Center.

I would add another general consideration which will have major bearing on the scientific content of the first Apollo missions. The nature of the scientific investigations which can be undertaken will differ greatly if the Apollo crew is comprised totally of <u>astronauts</u> whose primary mission and training are the safe navigation of the Apollo spacecraft and the lunar landing capsule compared with the research which may be undertaken if a scientist can be included in the mission. There can be no debate that the scientific accomplishments of the first manned missions to the Moon could profit enormously by the inclusion in the crew of a scientist who was also trained as an astronaut. Moreover, scientists throughout the country are agreed that it is possible to find scientists who can readily qualify for astronaut training, while it goes without saying that to train an astronaut to the scientific maturity and judgment which would be required for the maximum research program in the primordial environment of the Moon is an enormously more difficult task. I might add that in view of my own background as an aviator in the U. S. Navy for 38 years, I can see utterly no reason why qualified scientists cannot also be qualified as astronauts.

In addition, there seems little room for dissent that a scientist's participation in lunar exploration is essential when it becomes technologically feasible to include him. A mature scientist will be required to make a rapid interpretation of the broad situations which he encounters and prompt selection of alternate courses of action, study and investigation. Consequently, he will contribute critical elements of scientific judgment and discrimination in conducting the lunar exploration that can never be supplied by any other means. Moreover, on the basis of this scientific sophistication and judgment it is likely that the next and more detailed scientific investigations of the lunar surface will be based.

Based upon all of the foregoing premises I would say that the next most important scientific undertaking for the Apollo mission is a general survey of its surface characteristics. An experienced scientist should gather qualitative and quantitative information about the surface geometry and all of its apparent geological and geophysical characteristics. Of course, he should acquire as many representative samples as possible within the limits of his mobility. Lunar samples are of course extraordinarily important and both surface and sub-surface samples should be acquired if at all possible. Even from randomly selected samples an enormous amount of the most valuable scientific information will be obtained. It will be possible to undertake radioactive isotope examinations to determine the lunar geologic history; scientists can examine the samples for cosmic ray exposure history; examinations can be made of such characteristics as trace elements, gross magnetic composition, mineral content, physical properties, water of crystallization and many similar properties. These investigations will be enormously valuable in considering the origins and history of the Moon, and in a comparative way, in considering the history and origins of the solar system and the universe itself. Moreover, it is not impossible to hope that one could find highly organized organic elements indicative of ancient biota, a discovery that would have the most profound effects upon our knowledge of the origins and development of life. Without any doubt, such samples will control the planning for the next phase of lunar scientific measurements which should be undertaken.

Third, and presuming that time and weight constraints allow, I believe that the next priority of scientific investigations which should be undertaken is to plant scientific instruments which can telemeter back to Earth a prolonged series of information about lunar events. In this category fall such instruments as lunar seismographs, magnetographs, equipment to measure the thermal regime and conductivity of the lunar surface, radiation detecting devices, meteor detectors, and instruments to record such elements as its volcanic and tectonic activities. Precise and continuous distance measurement should not be ignored.

In reply to your specific inquiry, I do not have many suggestions regarding publications which you should consult in your study. Mr. Peavey informs me that you have already written to Mr. Hugh Odishaw for recommendations from the Space Science Board of the National Academy of Sciences. This contact should be pressed, for the Board's views would be most valuable and many studies of these matters have been made. In particular you should be careful to study in detail the Academy Publication 1079, "A Review of Space Research" which reports on a detailed eight-weeks Board study of space research conducted in the summer of 1962. You should also examine carefully "Science in Space" edited by Berkner and Odishaw, and published by McGraw Hill in 1961.

Finally, I should like to offer all assistance which the Graduate Research Center can extend to you in this most important study for the Manned Spacecraft Center. I am aware that you have been in contact with some of our staff and that copies of your letter to me were forwarded to Professors Hales and Johnson. I hope that you will call upon us further as seems desirable to you; we are ready to assist and help whenever you may call upon us.

Sincerely yours,

L. V. Berkner
President

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER

INSTITUTE FOR SPACE STUDIES
NEW YORK, N. Y.

MAIL ADDRESS
INSTITUTE FOR SPACE STUDIES
475 RIVERSIDE DRIVE
NEW YORK 27, N. Y.

TELEPHONE
UNIVERSITY 6-3600

November 29, 1963

Drs. K.R. Van Lopik and R.A. Geyer
Texas Instruments Incorporated
Science Services Division
100 Exchange Park North
Dallas, Texas

Dear Drs. Van Lopik and Geyer:

With regard to scientific experiments to be performed in association with the Apollo lunar landings, I may say that I am in general agreement with the conclusions reached in the Sonett committee study. However, the suggested experiments in that group are sufficiently numerous that some question arises as to desirable priorities. I believe that to the maximum extent possible it is desirable that the scientific phases of the Apollo mission should be left as flexible as possible until the last possible moment. Presumably the results of the Ranger and Surveyor studies will provide an important input into the Apollo scientific program. I doubt that it is desirable at the present time to think much beyond the first mission or two. It seems to me that during such a mission the primary interests of the astronauts will be toward their return journey rather than toward their ability to carry out exploration in the lunar environment. Even the relative ease of getting out of the spacecraft and working on the surface of the moon must be considered highly uncertain until the results of the first Surveyor landings on the moon are at hand.

However, I would state the following: I believe that if it is possible for the earliest Apollo astronauts to operate in the lunar environment at all, their first tasks should be to select a representative group of samples to be returned to earth for laboratory analysis. They should have detailed geological coaching in the selection of these samples, and if possible should also receive advice from the earth while they are in the moon regarding the selection of the samples, particulary if television links are available so that ground based geologists may be able to evaluate the situation to some extent. It would also be very desirable to have the astronauts photograph in extensive detail the sites from which the samples have been removed both before and after the removal. It is to be hoped that the astronauts will be able to select their samples from beneath whatever dust cover blankets the ground.

Yours sincerely,

Alastair Cameron

A.G.W. Cameron

AGWC:es

Lamont Geological Observatory of Columbia University | *Palisades, N.Y.*

CABLE ADDRESS: LAMONT, PALISADES, N.Y. Code 914, ELmwood 9-2900

26 November 1963

Texas Instruments Incorporated
Science Services Division
100 Exchange Park North
Dallas, Texas

Dear Sirs:

With reference to your letter of 25 October 1963, I do not believe that there is much that I can add at this time to the thoughts I have already expressed in the publications and reports to which you referred.

I believe that the suite of experiments already planned by the Space Sciences Division of NASA, for the unmanned lunar expeditions, is a fairly good starting point for the types of experiments which might be profitably carried out by manned expeditions. It appears that there are three principal advantages to manned experiments:

1) Intelligent observation

2) Intelligent sample collection

3) Intelligent instrument implantation (either for passive or active experiments)

Any scientific program conducted during manned expeditions should exploit these advantages to the fullest extent.

I believe one of the earlier astronauts should be an experienced field geologist with sufficient background in geophysics and geochemistry to obtain useful samples and properly install experimental apparatus.

I hope that these thoughts are of some use to you in your work.

Sincerely yours,

Maurice Ewing

Maurice Ewing

ME:lw

UNIVERSITY OF LONDON OBSERVATORY

TELEPHONE: MILL HILL 1618

MILL HILL PARK
LONDON N.W.7

19th November, 1963.

Messrs. Van Lopik and Geyer,
Science Services Division,
Texas Instruments Inc.,
100 Exchange Park North,
Dallas,
Texas,
U.S.A.

Dear Messrs. Van Lopik and Geyer,

In reply to your letter of 14 November it seems that the Item 2 list of your work statement covers all the important initial measurements.

Of these items I should select:

(1) surface photography (geometry of macro-relief if your list uses macro-relief in its geological sense, which is normally applied to specimens that may be held in the hand and viewed with the unaided eye),

(2) nuclear (radioactive, in particular) measurements,

(3) age determinations

(4) investigation of stratification,

placing (1) in the position of maximum interest and (2) second. This is allied to (3), and both (2) and (3) should, of course, to derive most benefit, be conducted not only at a small depth beneath the surface, but also at as great a depth as is feasible (presumably by drilling and lowering a gamma-ray counter); hence the suggestion (4). I am assuming that the location of the instrument packet is fixed and known.

In selecting these topics I have taken into consideration the fact that some of the other problems, although no less important scientifically, are subject to successful attack from other directions. All except the simplest on-the-spot studies of composition and rheology are in my view going to be too specific to be worth a great deal of initial effort. An exception, possibly, is the determination of elemental abundances at depth. I am certain that there are volcanic or igneous rocks on the Moon, and specific compositional analyses conducted at a lunar impact site could therefore be misleading. If stratification

continued.......

is to be studied, the drill itself could be instrumented to act as a penetrometer.

Studies from a distance seem to me to indicate a general situation in which the lunar soil acts as though it had only a small angle of internal friction. I think the bulk of the evidence we have points to a spongy structure for the lunar top-soil. I am inclined to the conservative view that the bearing strength of the soil is low, and it would never occur to me to try to land a man on the Moon until this point, at least, had been settled first by unmanned probes.

I hope that these few comments may be of use to you.

Yours sincerely,

Gilbert Fielder

G. Fielder.

Enclosures: Fielder, Dr. Gilbert, 1963, Nature of the Lunar Maria: Nature, Vol. 198, No. 4887, pp. 1256-1260, June 29

Fielder, Dr. Gilbert, 1963, Terrestrial oceanic ridges and the Lunar Mare ridges: Nature, Vol. 199, No. 4892, p.473 3 August.

Fielder, Dr. Gilbert, Lunar Section, Project Moonhole: Journal of the British Astronomical Association, Vol. 73, No. 2

Fielder, Dr. Gilbert, Lunar Section, Lunar Slopes: Journal of the British Astronomical Association, Vol. 72, No. 8

Fielder, Dr. Gilbert, Lunar Tectonics: Quarterly Journal of the Geological Society of London, Vol. 119, pp. 65-94, 5 April 1963

Fielder, Dr. Gilbert, and Jordan, Carole, 1962, Selenological implications drawn from the distortions of craters in the Hipparchus region of the moon: Planetary Space Science, Vol. 9, pp. 3-9.

Fielder, Dr. Gilbert and Warner, Brian, 1962, Stress systems in vicinity of lunar craters: Planet. Sp. Sci. Vol. 9, pp 11-18

CORNELL UNIVERSITY

ITHACA, NEW YORK

Center for Radiophysics and Space Research
Phillips Hall

October 29, 1963

Dr. Jack R. Van Lopik
Dr. Richard A. Geyer
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Drs. Van Lopik and Geyer:

Thank you for your letter inquiring about material and views concerning lunar surface exploration to be done in the Apollo program. I am very glad to learn that you are undertaking this survey which many people associated with the space field have thought to be an urgent requirement. I have had an opportunity to think about the points you raise, not only in connection with our work here concerning the lunar surface but also in connection with various government committees on which I sit.

I am sending you a preprint of a review paper which sums up my views concerning all the evidence derived from observations other than an examination of the optically discernable features. So far as the latter are concerned, I don't think that much can be added at the present time to the discussion that is in the literature, although I recognize that many people are trying to make such additions.

I will assemble what material I can in reply to your questions in the course of the next two weeks. If you think that a meeting would be helpful, and if you are likely to be in the New York region in the near future, please let me know. I myself propose to be in Dallas from December 16-18 but I presume that your plans call for a faster time schedule.

Yours sincerely,

T. Gold
T. Gold
Director

TG:JZ
Encls.

Enclosure: Gold, T., 1963, Structure of the Moon's Surface: NASA Grant NsG-382

CORNELL UNIVERSITY

ITHACA, NEW YORK

Center for Radiophysics and Space Research
Phillips Hall

November 8, 1963

Dr. Jack R. Van Lopik
Technical Director
Apollo Study
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Dr. Van Lopik:

Would you like to pay us a visit here around the time of your New York trip? You can comfortably make it over the day (Ithaca is 1-1/2 hours by air from New York). This would allow you to talk also to my colleagues and to see various informative experiments and demonstrations concerning the behavior of powders in a vacuum and other lunar circumstances.

It would not be easy for me to come to New York that week because of teaching commitments here, but I would be available for most of the day on any of the days that week (November 18-23).

Yours sincerely,

T. Gold
Director

TG:MEZ

CORNELL UNIVERSITY

ITHACA, NEW YORK

Center for Radiophysics and Space Research
Phillips Hall

November 26, 1963

Mr. Jack R. Van Lopik
Technical Director
Space and Environmental Sciences
Texas Instruments Incorporated
100 Exchange Park North
Dallas, Texas

Dear Mr. Van Lopik:

Herewith my notes taken during our discussion, in case they are of use to you.

I may now not be in your part of the world on December 16 and would regret not seeing you then.

Yours sincerely,

T. Gold

T. Gold
Director

TG:MEZ
Encl.

POINTS OF EMPHASIS FOR APOLLO INVESTIGATIONS

1. Electrostatics

1.1 Training of astronauts in circumstances of vacuum, rock dust and electrostatic effects. The astronauts should be made thoroughly familiar with all the unusual effects that can be expected to result from electric charges on equipment that is brought to the moon and on grains of dust that may be loosened by activities taking place. Such effects may be damaging to optical surfaces, solar cells, delicate mechanisms and air-tight seals in the open condition. A study and training program should therefore be instituted by people experienced in these fields to include a great variety of vacuum dust and electrostatic effects.

1.2 All surfaces that are to be optically transparent must have a conductive coating to minimize the electrostatic potentials that may occur. This is no guarantee of avoiding trouble, but certainly it is better than to leave the chance potentials that dielectric materials may otherwise possess.

1.3 A device for changing the electrostatic potential of an astronaut in a spacesuit or of the landed vehicle may be desirable. This may consist of a stick and handle with a source of potential difference between them. The stick may be stuck into the ground or it may suffice to leave it merely conducting to the plasma in space.

2. Problems related to the Spacesuit

2.1 What is the temperature of the hottest rocks that the astronauts might come into contact with? This is likely to be considerably hotter than the mean daytime temperature. This is of importance particularly with respect to the gloves of the spacesuit which must be able to stand up to those temperatures on contact.

2.2 How much adhesion of dust to itself and to the astronauts is to be expected? Does it tend to clog underfoot in such a way as to impede walking?

2.3 Some dust is likely to be brought back into the LEM. Even if electrostatic precipitators are used, it may be unavoidable that some dust will remain free and later in gravity-free surroundings may drift into mechansims. All LEM instrumentation must therefore be designed so as to be unaffected by dust inside the vehicle.

3. Photography

The planning of photography done by the astronauts is of utmost importance for the success of the scientific mission. A large proportion of the valuable scientific information may be brought back in the form of high-quality photographs, optimizing all the circumstances. The design of a camera and the training of astronauts for this is therefore of great importance.

I would suggest that the camera specifications should be as follows: It should be a stereo camera loaded with color film with an electric rapid film wind, and with either enough film for several hundred frames or a quick reload device. The exposure should be determined in daylight by an exposure meter, but each time the trigger is pressed the camera should automatically take three pictures: one with an exposure greater than that indicated by the meter, the other with the value indicated and the third with a lesser value. This would allow later information to be obtained from the brightest and the darkest areas within the picture which would usually not be possible, especially in the harsh lighting conditions on the moon, with any single value of the exposure. In the case of nighttime illumination artificial lights should be used in such dispositions as to optimize the visibility of surface structure which is in fact expected to be rather unfavorable for photography.

Such a camera will have to have a minimum of external adjustments and it will be difficult to design it so that it may be handled well by the astronaut's gloves. It will, of course, have to stand up to vacuum conditions and will have to have the appropriate temperature control. It will be necessary to be quite sure of its function and it should therefore be equipped with a read-out of light having fallen on an area adjacent to the film to certify that an exposure has been made and a read-out to certify that film transport has been accomplished, rather than merely the usual interlock.

Such a camera is a formidable problem in camera engineering if one aims, as one should, at an extremely high reliability, convenience and speed of handling, and an extremely high quality. It is a project that should be undertaken early so that a long period would be available for practice and improvements and the development of associated techniques. The astronauts should have very extensive training in photography, both in the technical handling of that camera and in the judgment of scenes to be photographed and the visibility of features that will result. The bringing back of lunar samples and the bringing back of a great number of high-quality pictures should be the main areas of the training that they will receive for scientific work on the lunar surface unless they can be real professional scientists.

4. Survey

In addition to the obvious survey of local topography in their surroundings, they should survey the ground structure wherever possible by the use of a rod that can be hand drived into the ground. If the ground is composed of agglomerates of dust, as seems likely, it is important to discover whether there are internal voids or caverns and whether there are "snow drifts" in certain localities. Such a survey may be necessary to avoid difficulties or disasters.

If there are any natural fissures or cracks they should of course be explored and subsurface samples be taken from them (the survey and sample techniques have been discussed many times before and are of course vital but need not be mentioned here again.).

T. Gold

November 22, 1963

5 November 1963

Dr. Jack R. Van Lopik
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Jack:

I am informally answering your formal letter (and Geyer's) of 28 October in re. the geologic - geophysical studies and experiments for Apollo. Yes, we will be happy to contribute. I say "we" because two or three of the engineers in our extraterrestrial section will also be concerned. We'll have a few skull sessions shortly and forward the results, hopefully of value.

Sincerely,

B. M. Hall

BRUCE M. HALL

AIR MAIL

HEADQUARTERS
DEPARTMENT OF THE ARMY
OFFICE OF THE CHIEF OF ENGINEERS
WASHINGTON 25, D.C.

IN REPLY REFER TO
ENGMC-ED

15 November 1963

Dr. Jack R. Van Lopik
Dr. Richard A. Geyer
Technical Directors, Apollo Study
Texas Instruments, Inc.
P. O. Box 35084
Dallas, Texas

Dear Dr. Van Lopik and Dr. Geyer:

As requested in your letter of 28 October, inclosed is a generalized study on the problem of Apollo team tasks while on the lunar surface. As noted, the subject of task equipment or equipment use techniques has not been included.

We wish you success in your interesting study.

Sincerely yours,

B. M. Hall
BRUCE M. HALL
Geologist

1 Inclosure
as stated

ENGMC-ED

15 November 1963

MEMORANDUM FOR RECORD

SUBJECT: Suggested On-Site Lunar Experiments for Accomplishment by Apollo Personnel

1. Reference letter from Texas Instruments (Van Lopik and Geyer) to Mr. Bruce M. Hall, subject as above.

2. The subject letter requested assistance in formulating exploration tasks for Apollo personnel and in establishing their priority sequence. These tasks were to be effected by the following constraints:

a. Time - 2 to 24 hours

b. Environment - lunar

c. Weight - experimental equipment

d. Safety - astronaut and mission equipment

e. Efficiency - for present and future operations

3. The following tasks are presented in a priority arrangement based on successive considerations of safety, future operations, materials-environment interaction, and, lastly, scientific interest. No attempt is made to describe equipment or methods of use.

<u>Task No. 1</u> - <u>Radiation Levels</u>

Prior to exit from the landing craft, immediate concern will be radiation; its nature and its probable effect on human tissue. Secondary concern would be applied to radiation source.

<u>Task No. 2</u> - <u>Meteorite Infall</u>

The incidence of infall of solid materials (primary and secondary) should be determined. Data should include particle sizes, frequency and energy.

<u>Task No. 3</u> - <u>Trafficability</u>

High priority should be alloted to trafficability problems. Initially this would be restricted to individual locomotion but later to soil properties affective in lunar wheeled transportation.

Incl 1

Task No. 4 - Photography

Photographic and photometric observation should be had from all possible observation points.

Task No. 5 - Soils Exploration

Vertical drilling and sampling to determine depth, stratification, temperature gradient, and on-site soil mechanics properties.

Task No. 6 - Dust Collection

It has been postulated that under the high vacuum conditions on the lunar surface electrostatically charged dust particles dislodged from the lunar surface by meteoroid impacts will adhere to structural surfaces. This condition, in a given time, may reduce the effectiveness of solar reflectors, solar cell panels, power equipment radiators, and normal radiation cooling allowed in the design of power components and systems. An on-site study is necessary to determine if this condition exists, the rate of accumulation as a function of time, and the effect of this accumulation on the optical and thermal and electrical characteristics of structural surfaces.

Task No. 7 - Shielding (Radiation)

Lunar surface material should be analyzed to determine its characteristics and effectiveness in shielding a reactor or shelter installed on the lunar surface.

Task No. 8 - Surface Thermal Characteristics

This task consists of tests for thermal conductivity and thermal diffusivity of lunar "soil". These have engineering application to burying of structures and equipment beneath the lunar mantle.

Task No. 9 - Electrical Conductivity of Lunar Surface Materials

The electrical conductivity of lunar soil may be sufficiently low so that grounding of electrical apparatus may be impossible. Also, a low electrical conductivity of soil may preclude the need for insulation of buried or exposed cables. These factors are important considerations in the design and operation of a lunar electrical power system. Simple tests on soil samples (collected from the lunar surface) could provide the necessary data.

Task No. 10 - Chemical composition of the soil and/or rock

Purpose - scientific and extraterrestrial resources investigation

Task No. 11 - Acceleration due to gravity

A several-point determination of the lunar gravity "constant".

Task No. 12 - Seismograph Installation

Set up and place in operation several self-sufficient seismographs, instrumented for remote telemetering.

HALL

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER

INSTITUTE FOR SPACE STUDIES
NEW YORK, N. Y.

MAIL ADDRESS
INSTITUTE FOR SPACE STUDIES
475 RIVERSIDE DRIVE
NEW YORK 27, N. Y.

TELEPHONE
UNIVERSITY 6-3600

November 11, 1963

Dr. Jack R. Van Lopik
Science Services Division
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Dr. Van Lopik

I was very interested in the letter which you and Dr. Geyer sent recently regarding the experiments to be performed on the lunar surveys during the Apollo program.

At the present time I have no suggestions to offer in this regard, but I believe that Dr. A.G.W. Cameron, who has been actively engaged in theoretical studies relating to lunar history, may have some important suggestions to make. I am therefore taking the liberty of forwarding a copy of your letter to him with the suggestion that he reply directly.

With best wishes,

Sincerely,

Robert Jastrow
Director

RJ:blr

The RAND *Corporation* 90406

1700 MAIN STREET
SANTA MONICA, CALIFORNIA

1 November 1963

WILLIAM W. KELLOGG
HEAD, PLANETARY SCIENCES DEPARTMENT

Mr. Jack R. Van Lopik
Mr. Richard A. Geyer
Texas Instruments Inc.
100 Exchange Park North
Dallas, Texas

Gentlemen:

In answer to your letter of October 25 concerning suggested observations and experiments to be performed on the Moon during the Apollo program, I do not feel that I can add anything significant to the many statements that have already been made on this subject. Although it is not the most recent thing on the subject, I would call your attention to a review of this question in the National Academy of Sciences-National Research Council Publication 1079, "A Review of Space Research." In Chapter 4 entitled "Lunar and Planetary Research," the views of a number of scientists who spent the better part of the summer of 1962 at the University of Iowa discussing this subject are given.

I wish you every success in your project, and hope that you can suggest how scientific observations can be most effectively made during the early part of the Apollo program.

Sincerely yours,

Wm. W. Kellogg

W. W. Kellogg

WWK:cs

TELEPHONE: ARDWICK 3333

DEPARTMENT OF ASTRONOMY,
THE UNIVERSITY,
MANCHESTER, 13.

ZK/DA.

5th November, 1963.

Dr. Jack R. Van Lopik, and Dr. Richard A. Geyer,
Technical Directors,
Apollo Study,
Texas Instruments Incorporated,
Science Services Division,
100 Exchange Park North,
DALLAS, Texas.

Gentlemen;

Your letter of October 25th was very welcome. I appreciate the importance of the task which you have been assigned in the frame-work of the lunar Apollo project, and should be glad indeed to assist you in your plans, to the best of my ability.

It would help me in this connection if you could indicate to me the specific questions which are of interest to you. I do not quite know what your principal problems are; but if you would inform me of them in more specific terms, I should be glad to answer your questions to the best of my ability, or give reference to pertinent literature.

Sincerely yours,

Zdenek Kopal

Zdenek Kopal.

CALIFORNIA INSTITUTE OF TECHNOLOGY
DIVISION OF THE GEOLOGICAL SCIENCES

SEISMOLOGICAL LABORATORY
PASADENA

ADDRESS:
SEISMOLOGICAL LABORATORY
220 NORTH SAN RAFAEL AVE.
PASADENA, CALIFORNIA

November 15, 1963

Mr. Jack R. Van Lopik
Technical Director, Apollo Study
Texas Instruments Incorporated
100 Exchange Park North
Dallas, Texas

Dear Jack:

Frank Press has asked me to reply to your request for important types of data to be obtained by a lunar astronaut.

Two types of seismic missions are thought to be of basic importance for the solution of lunar problems. The first is to conduct an active seismic refraction experiment to explore the near surface layers of the Moon. With our proposed technique this would take 1-2 minutes execution time. The estimated weight of this scientific package would be of the order of 30 lbs. The second basic experiment is to emplace a 3-component long-period seismograph (estimated weight of our instrument - 10 lbs.) on the lunar surface for long-term operation after the astronaut departs. This instrument would take 1-2 minutes to emplace and would probably be emplaced just before departure.

I hope that our opinions will be of some use to you.

Sincerely yours,

Robert L Kovach

Robert L. Kovach
Research Fellow

RLK/rw

cc Frank Press

THE UNIVERSITY OF ARIZONA
TUCSON

LUNAR AND PLANETARY LABORATORY

29 October 1963

Messrs. Jack Van Lopik and Richard Geyer
Technical Directors
Apollo Study
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Gentlemen:

Many thanks for your letter of October 25. Our scientific results are published in the Communications of the Lunar and Planetary Laboratory, which we have the pleasure of sending you under separate cover.

We shall always be pleased to receive members of your group for consultation on work and progress.

Sincerely yours,

Gerard P. Kuiper

Gerard P. Kuiper
Director

GPK:ie

Received under separate cover:

Jacchia, Luigi G., 1963, Meteors, Meteorites, and Commets: Interrelations: Reprinted from Middlehurst and Kuiper: The Moon, Meteorites, and Comets, The University of Chicago Press.

Arthur, D.W.G., Agnieray, Alice P., Horvath, Ruth A., Wood, C.A., and Chapman, C.R., 1963, The system of lunar craters, Quadrant I: Communications of the Lunar and Planetory Laboratory, Volume 2, No. 30.

HEADQUARTERS
AERONAUTICAL CHART AND INFORMATION CENTER
UNITED STATES AIR FORCE
SECOND AND ARSENAL
ST. LOUIS ~~18~~, MISSOURI 63118

14 NOV 1963

Science Services Division
Texas Instruments Corporation
Attn: Messrs. Van Lopik & Geyer
100 Exchange Park North
Dallas, Texas

Gentlemen

Reference is made to your letter of 25 October addressed to Mr. Robert Carder requesting our views on the cartographic requirements associated with Project Apollo.

Your interest in contacting ACIC is appreciated, but due to heavy demands made upon our limited lunar capability we are not in a position manpower-wise to assist in your study at this time.

Sincerely

Benjamin B. Lane

BENJAMIN B. LANE, Jr.
Acting Technical Director

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FILE
DEC 3 1963

AIR MAIL

Dr. Jack R. Van Lopik
Science Services Division
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Dr. Van Lopik:

I am very interested to hear of your study contract for the Apollo mission, and would be glad to make a few suggestions. I would like to stress that the following comments are personal opinions, and do not represent official NASA or GSFC policy, nor should you take them as any sort of directive.

I should like to comment, in order, on what I conceive to be the main objective of the Apollo landings, on criteria for proposed experiments, and finally on some possible scientific operations.

First, it seems to me that the prime scientific objective of the early Apollo landings should be to learn more about the moon itself; i.e., investigations should be focussed on the moon, rather than using it as a base. This would tend to rule out astronomical observations as such during the early landings, although presumably they will be an important part of the later lunar program.

To insure the maximum information retrieval, the following principles might be stressed:

1. Scientific operations should be scheduled so that if, after landing, it becomes necessary to abort the mission and return before the expected time, the mission will be at least partly successful. One example of how this principle might be applied would be the continual transmission, in real time, to earth of observations made during the surface operations.

2. The widest possible variety of terrain and rock types should be examined. This would, in principle, entail emphasis of extensive though simple observations rather than intensive observations of a small area.

3. Over-complicated and time-consuming activities should be eliminated from consideration if they will seriously compromise accomplishment of the basic activities. Past experience shows that the most successful operations in strange environments are the simplest.

I suggest that any observation or experiment considered for inclusion on the Apollo missions be judged according to the following check list, which is designed to serve as a sieve. The value of proposed activities could be judged according to the degree to which these questions can be answered "yes."

1. Is it of basic and permanent scientific value?

   Note - "Basic" means related to the solution of problems such as the origin of the solar system or the evolution of the earth; "permanent" means not likely to be made obsolete or unnecessary by other experiments to be made in the foreseeable future.

2. Can it be done only on the moon, or done best on the moon?

   Note - This is designed to eliminate activities which can be done by any device merely placed in the vicinity of the moon, such as a lunar satellite, or by any spaceborne device, such as those carried by a MOL, OAO, or other earth satellite. The experiment must fit logically into the mission framework.

3. Can it be done only by a man or done significantly better by a man?

   Note - This is intended to exclude measurements or observations which could be made by soft-landing unmanned probes such as Surveyor or its successors.

4. Is it valuable for future scientific lunar activities or for future operational purposes?

   Note - Many valuable activities are inherently closed-end, i.e., they are intended to answer a yes-or-no question. However, when all other factors are about equal, priority should be given to activities which are important to future planning and operations.

Based on the foregoing, I suggest that the most important scientific activities which the crew can perform would be:

1. Sampling the lunar surface.

2. Close observation of surface features.

3. Emplacement of instruments which cannot practically be landed by unmanned probes.

In detail, these activities might be carried out by surface traverses planned in advance to cover the greatest possible variety of terrain. The astronaut should begin sampling and reporting observations of surface conditions immediately on leaving the LEM, and continue these operations throughout the traverse. Photographs should be taken at frequent intervals along the traverse; real-time TV for relay to the CM or to earth might be worthwhile.

At a suitable time, an instrument package would be emplaced on the surface and/or in a shallow drill hole. Instruments should be of the passive type and require little astronaut manipulation; possibilities include seismograph-gravimeter, Bullard-type thermal probe combined with conductivity measurement, magnetometer, and radiation detector. They should be designed to transmit data for an extended period after the LEM leaves. If possible, the instrument package might be built so that it could be simply dumped on the surface and turned on, if this were made necessary by some emergency requiring a quick return.

I hope these comments will be of some use in your work. Let me stress again that they represent personal opinion and, of course, do not restrict you in any way.

Sincerely yours,

Paul D. Lowman, Jr./gmd

Paul D. Lowman, Jr.

2101 CONSTITUTION AVENUE
WASHINGTON 25, D. C.

CABLE ADDRESS: NARECO
WASHINGTON, D. C.

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
OF THE UNITED STATES OF AMERICA

SPACE SCIENCE BOARD

November 5, 1963

Mr. Richard A. Geyer
Mr. Jack R. Van Lopik
Science Services Division
Texas Instruments Inc.
100 Exchange Park North
Dallas, Texas

Dear Sirs:

I am writing in response to your letter of 25 October concerning the scientific investigations which might be made on the lunar surface during the Apollo program. The Space Science Board's present views on this subject are contained in "A Review of Space Research" (NAS Publication 1079), particularly Appendix I to Chapter II, and have not been expanded since publication of that report. The more general aspects of lunar research discussed in Chapter 4 are also relevant.

I hope that you will find this reference useful.

Sincerely yours,

Hugh Odishaw
Executive Director

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

NOV 7 1963

Dr. Jack R. Van Lopik
Dr. Richard A. Geyer
Technical Directors
Apollo Study
Texas Instruments Inc.
100 Exchange Park North
Dallas, Texas

Dear Messrs. Van Lopik and Geyer:

The publications which give the best account of our views in this office are the following:

(a) J. A. O'Keefe and W. S. Cameron, Evidence from the Moon's Surface Features for the Production of Lunar Granites, <u>Icarus 1</u>, 271-285.

(b) P. D. Lowman, Jr., The Relation of Tektites to Lunar Igneous Activity, <u>Icarus 2</u>, No. 1, 35, 1963.

(c) The book, <u>Tektites</u>

(d) W. S. Cameron, An Interpretation of Schröter's Valley and Other Lunar Sinuous Rilles, <u>J.G.R.</u> (in press), <u>Sky and Telescope XXVI</u>, No. 1, 21, 1963 July (short version).

It is my opinion that measurements made on the surface of the moon should take into account the fact that lunar surface materials are also present at the surface of the earth. Hence the problem is rather one of identification than the chemical analysis of a totally unknown material. Any long range program for the study of the moon's surface should take into account the new point of view which will result when lunar surface material is successfully identified. This means that relatively unsophisticated experiments designed to measure the amount of silicon or oxygen would stand a very good chance of becoming obsolete before they are tried. I feel that the return of a lunar sample is the single most important experiment that could be carried out on an early lunar mission. I would be glad to send some more details if you could reduce the scope of the question a little bit. Have you seen the results of the studies of the NASA subcommittees on these problems?

Sincerely yours,

John A O'Keefe

John A. O'Keefe
Assistant Chief
Theoretical Division

SMITHSONIAN INSTITUTION
ASTROPHYSICAL OBSERVATORY

OFFICE OF THE DIRECTOR
ASTROPHYSICAL OBSERVATORY
60 GARDEN STREET
CAMBRIDGE 38, MASSACHUSETTS

14 November 1963

Mr. Jack R. Van Lopik
Geosciences Department
Science Services Division
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Mr. Van Lopik:

While I do not perform free consultation services, I am pleased to send reprints. Enclosed are three reprints of possible relevance to Apollo lunar geology.

Sincerely,

Carl Sagan

Carl Sagan reg.

CS/reg
Enclosures (3)

Sagan, Carl, 1963, Prospects for lunar organic matter: Bulletin of Virginia Polyt. Ins. Vol LVI, No. 7, May, 1963

Sagan, Carl, 1960, Biological Contamination of the moon: Nat. Acad. of Science, Vol. 46, No. 4, April

Sagan, Carl, 1960, Indigenous organic matter of the moon: Nat. Acad. of Science, Vol. 46, No. 4, April

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

CENTER FOR ATMOSPHERIC
AND SPACE PHYSICS

October 31, 1963

Dr. Jack R. Van Lopik
Texas Instruments Incorporated
100 Exchange Park North
Dallas, Texas

Dear Dr. Van Lopik;

The enclosed reprints will give you a general idea of my thinking on the subject of the lunar surface.

Sincerely yours,

S. F. Singer
Professor of Physics and Director,
Center for Atmospheric and Space Physics

SFS:jw

encl.

Opik, E.J., 1960, The lunar surface as an impact counter: Royal Astronomical Society, Vol. 120, No. 5, pp. 404-411.
Opik, E.J, and Singer, S.F., 1960, Escape of gases from the moon: Journal of Geophysical Research, Vol. 65, No. 10, October
Opik, E.J., 1961, Notes on the theory of impact craters: Substance of these notes given at Cratering Symposium, Geophysical Laboratory, March 28-29, 1961.
Singer, S.F., and Walker, E.H., 1962, Photoelectric screening of bodies in interplanetary space: Icarus, Vol. 1 No. 1, May
Singer, S.F., and Walker, E.H., 1962, Electrostatic dust transport on the lunar surface: Icarus, Vol. 1, No. 2, September
Opik, E.J., 1962, Surface properties of the moon: Chapt. V., Progress in the Astronautical Sciences, Vol. 1, edited by S.F. Singer, North-Holland Publishing Company, Amsterdam.
Opik, E.J., 1962, The lunar atmosphere: Planet. Space Sci., Vol. 9, pp. 211-244.

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California

November 6, 1963

Drs. J. R. Van Lopik and R. A. Geyer
Texas Instruments Inc.
100 Exchange Park North
Dallas, Texas

Gentlemen:

As you know, we have been working for several years in delineation of lunar and planetary problems and the values and priorities of various planetological experiments including geological duties of the first lunar astronaut. When this information is published in final form, I shall forward you the material.

Yours truly,

R C Speed

R. C. Speed

RCS:raf

Telephone 354-4321 Twx 213-449-2451

UNIVERSITY OF CALIFORNIA, SAN DIEGO

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SCHOOL OF SCIENCE AND ENGINEERING

P. O. BOX 109
LA JOLLA, CALIFORNIA 92038

November 1, 1963

Dr. Jack R. Van Lopik
Dr. Richard A. Geyer
Geosciences Department
Texas Instruments, Inc.
100 Exchange Park North
Dallas, Texas

Dear Drs. Van Lopik and Geyer:

Under separate cover I am sending you a group of my reprints. It is my plan in the near future to write up my ideas about the origin and the structure of the moon, etc., summarizing some of the things that I have said before.

With best regards,

Very sincerely,

Harold C. Urey

Harold C. Urey

P.S. The 6th paper gives the best summary of ideas in regard to the moon.
HCU

Enclosure: Urey, H.C., 1963, Reprints of some papers by H.C. Urey on the origin of the solar system and on the origin, history, and structure of the moon: University of Calif., San Diego, La Jolla, California.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA 35812

IN REPLY REFER TO:
DIR

NOV 29 1963

Messrs. Jack R. Van Lopik
and Richard A. Geyer
Technical Directors
Texas Instruments Inc.
Science Services Division
100 Exchange Park North
Dallas, Texas

Dear Sirs:

I regret that my answer to your letter of October 25 has been so long delayed. I have had an extremely heavy travel schedule and, as a result, my correspondence has suffered badly.

If, as you say in your letter, you are familiar with our previous publications in the field and the testimonies that have been presented on the Hill and other documents, there is probably very little I can add to what you already have accumulated. I suggest that you use the reports which have been written about the scientific programs of the Ranger and the Surveyor projects as one basis for your studies. Those reports contain the fallout of accumulated thinking on scientific missions of the past few years. You may emphasize in your study the requirement that your scientific program should be done in immediate connection with the astronauts, and only during the short period while the astronauts are on the moon.

As a further source of information, I am enclosing a copy of a report by A. H. Weber and G. C. Bucher of this Center. This report deals with scientific instrumentation in connection with an Apollo launch support vehicle.

Messrs. J.R. Van Lopik and R. A. Geyer

63

I anticipate that your study for the Manned Spacecraft Center will be of great value not only for the early lunar landings, but for some time to come.

Sincerely,

Wernher von Braun
Director

Enclosure

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

Dr. Jack R. Van Lopik
Texas Instruments Inc.
100 Exchange Park North
Dallas, Texas

Dear Jack:

I am taking it upon myself to answer your letter to John O'Keefe, a copy of which was kindly sent to me. Your efforts in obtaining opinions on the optimum measurements to be made on Apollo are greatly appreciated and, hopefully, some unanimity in the scientific community will make your job easier.

I am sure that many people will be willing to give advice on the observations to be made and therefore will limit mine to one facet--that of the collection of samples. First, the importance of sample collection cannot be underestimated, especially when geophysical measurements may seem more sophisticated and geological stratigraphy more glamorous. These two investigations, though quite important, will be meaningless without good petrologic control which, under the restricting conditions of lunar existence, will be impossible _in situ_. More important, however, is the fact that the petrology will be most informative about the history of the interior of the moon and the processes which have taken place there. Sample collection will be the first step in the study of the isotopic age determinations, differentiation trends and thermal history of the moon.

In view of the importance of sample collection, then, may I suggest you consider the following:

1. Sampling of meteoritic material deposited on the surface and interpreting it as lunar rock must definitely be avoided.

2. The samples must be as fresh as possible. They should not be from the vicinity of large craters and should be unaffected by solar radiation. Minor chemical and mineralogical peculiarities of the lunar rocks will be quite significant in the determination of the petrologic history and it would be impossible if the high pressure phases or the glass in the samples had been formed by impact or the bulk composition altered by fractional volatilization.

3. If there are layers on the moon--as Lowman suggest--which are due to emplacement of magma in lopoliths--then the most significant suite of samples--from the standpoint of petrologic history, would be taken from different places in a vertical section.

4. Putting all these factors together, the obvious solution is to drill for the samples. Obviously the political and technological considerations of such a program are imposing, but it will insure the significance of the samples returned. The alternative is to gamble on surficial samples being lunar material which has retained its mineralogical, isotopic and chemical composition and this, to me, seems a very poor bet.

I hope that you and the others will agree to this point of view. Best of luck in this very important work.

Very truly yours,

Louis S. Walter

cc: O'Keefe
Lowman

APPENDIX B

DEFINITION OF PROBLEM AREAS

APPENDIX B

DEFINITION OF PROBLEM AREAS

This appendix defines and discusses the five problem areas of lunar investigation which have been set up for the purposes of this report. These areas are Hazards, Trafficability, Lunar Basing, Lunar Surface, and Earth-Moon System. Each problem area defined is presented in table form, columned by fundamental classes and their importance indicated in the descending scale of ten to one. The problems themselves are a compilation of entries submitted by the study groups, and the scaling represents a consensus of the same groups. (This scale is different from that used in planning the missions.) The purpose of the material in this appendix is to provide a reference and cross-check for estimation of the importance of specific problems.

DEFINITION OF PROBLEM AREAS

Problem Area: Hazards

Fundamental Problems:

I. The astronaut can sink into or fall through something.

II. The astronaut can lose his balance and simply trip or fall.

III. Moving objects can hit, fall on or penetrate the astronaut's body.

IV. Some materials, by merit of their chemical or biological nature, can be deleterious to the astronaut.

V. The thermal environment can be hostile to the astronaut.

VI. The radiologic environment can be hostile to the astronaut.

VII. The astronaut can lose effective communication with the LEM.

	HAZARDS						
RANK	I SINKING OR COLLAPSE	II FALLING	III PROJECTILE	IV CHEMICAL AND BIOLOGICAL	V THERMAL	VI RADIOLOGICAL (INCLUDING UV AND VISIBLE)	VII COMMUNICATION AND MOVEMENT
10						Impairment of visual acuity and retinal burns (accidental direct viewing of sun)	
9		Sharp rock edges					Adhesion of electrically charged dust to astronaut and equipment
8	Falling into fissures covered by dust or otherwise concealed	Abrasive surfaces (extreme irregular micromicroterrain) Lunar lighting variations (shadows)	Flying debris from: Hammer blows Active seismic experiments				Impairment of radio communications equipment due to electrically charged surfaces
7	Collapse over near-surface voids as lava tubes and lava caves	Unstable rubble or dust-covered slopes		Pyrophoric dusts reactive in presence of oxygen and water on return trip Corrosion by reactive dusts or rock surfaces Handling and storage of explosives for active seismic work	Harmful heat radiation through spacesuit visor		Physical land obstacles to: Line-of-site communication with LEM Foot traverse
6						Skin burns on the face Radiation induced nausea, vomiting, leucopenia, hemmorrhage, infection, diarrhea, convulsions, and lethargy	

DEFINITION OF PROBLEM AREAS (CONTD)

	HAZARDS (CONT'D)						
RANK	I SINKING OR COLLAPSE	II FALLING	III PROJECTILE	IV CHEMICAL AND BIOLOGICAL	V THERMAL	VI RADIOLOGICAL (INCLUDING UV AND VISIBLE)	VII COMMUNICATION AND MOVEMENT
5		Steep slopes	Flying debris from lunar ejecta on meteoroid impact Mechanical puncture by micrometeroids		Cold welding or brittle fracture of boots or spacesuit with explosive decompression Thermal degradation of boots, spacesuit or LEM by pyrophoric or reactive dusts or rock surfaces	Sputtering damage to boots and spacesuit	
4	Collapse of bonded or cold-welded dust structures Engulfment in thick dust deposits	Mass movements (slumping, flow, etc.), natural or induced Cold welding or brittle fracture of spacesuit		Dormant but potentially dangerous life forms, particularly if released in earth environment	Heat conduction or loss at bootsole Thermal shock in going from irradiated to shadowed zones Metal fatigue induced by flexing as enhanced by the thermal environment	Water contamination by radioactive tritium	
3			Mass movements (avalanche, "landslide," etc.), natural or induced	Corrosive gases from volcanic vents and fissures			
2	Sinking in "quick" deposits		Active volcanic ejecta		Thermal degradation of boots, spacesuit or LEM by hot gases from volcanic vents and seeps Heat conduction or loss at LEM support leg		
1		Seismic ground motion					

DEFINITION OF PROBLEM AREAS (CONTD)

Problem Area: Trafficability

Fundamental Problems:

I. A pedestrian or vehicle can sink into or fall through the surface.

II. Vertical and sideward motion can impede forward progress.

III. Foreign objects, by collision or penetration, can impede progress.

IV. The chemical environment can impede progress.

V. The thermal environment can impede progress.

VI. The radiologic environment can impede progress.

VII. The mechanical environment can impede progress.

TRAFFICABILITY							
	I	II	III	IV	V	VI	VII
				Environment			
RANK	SINKING OR FALLING	VERTICAL AND SIDEWARD MOTION	FOREIGN OBJECTS	CHEMICAL	THERMAL	RADIOLOGICAL	MECHANICAL
10						Impairment of visual acuity and retinal burns	
9		Protuberances and depressions in path of vehicle (surface roughness)					
8					Cold welding or brittle fracture of moving parts	Radiation effects on electrical circuitry	Sharp rock edges Excessive wear at contacts of vehicle with surface
7	Falling into fissures covered by dust or otherwise concealed						Loss of traction
6	Mire or bog down in "quick" deposits Collapse of a thin crust over near-surface voids	Steel slopes and physical land obstacles		Corrosion by pyrophoric or reactive dusts or rock surfaces		Sputtering damage to exposed parts, especially those in contact with the surface	Vibration effects on vehicle parts
5	Collapse of bonded dust structures				Thermal degradation of vehicle by pyrophoric or reactive dusts or rock surfaces Thermal degradation of vehicle by the ambient temperature Effect on chemical stabilizing agents		

DEFINITION OF PROBLEM AREAS (CONTD)

TRAFFICABILITY (CONT'D)							
	I	II	III	IV	V	VI	VII
				Environment			
RANK	SINKING OR FALLING	VERTICAL AND SIDEWARD MOTION	FOREIGN OBJECTS	CHEMICAL	THERMAL	RADIOLOGICAL	MECHANICAL
4	Sinking in thick dust deposits	Mass movements (slumping, flow, etc.), natural or induced	Mechanical puncture by micrometeroids Lunar ejecta on meteroid impact				
3			Mass movements (avalanche; "land slide," etc.), natural or induced		Heat conduction or loss at contacts of vehicle with surface		Metal fatigue induced by flexing (especially as enhanced by the thermal environment)
2			Active volcanic ejecta	Corrosive gases from volcanic vents and seeps	Thermal degradation by hot gases from volcanic vents and seeps Volume changes or soil cracking due to frost heaving		
1		Seismic ground motion					

DEFINITION OF PROBLEM AREAS (CONTD)

Problem Area: Lunar Basing

Fundamental Problems:

I. What natural shelters are available for lunar bases?

II. Are potential sites suitable:
 A. In view of the geological environment?
 B. In view of the geophysical environment?
 C. In view of engineering problems and requirements ?
 D. In view of radiological environment?

III. Are lunar resources available for base support?

LUNAR BASING						
	I NATURAL SHELTER AVAILABILITY	II SUITABILITY OF POTENTIAL SITES				III LUNAR RESOURCES
RANK		A GEOLOGICAL ENVIRONMENT	B GEOPHYSICAL ENVIRONMENT	C ENGINEERING PROBLEMS AND REQUIREMENTS	D RADIOLOGICAL ENVIRONMENT	
10	Lava caves		Thermostating and design requirements	Foundation stability		
9		Surface geometry				Shielding materials
8	Pressure ridge fractures	Nature and location of bedrock				Heat sources (fumaroles, sofoteras, salses) Construction materials Lunar water resources: volcanic vents, seeps, and magmatic water
7	Small volcanic craters Lava tubes	Unstable slopes (possibility of slumps, slides, and rock falls especially due to excavation) Composition of ground materials Bonding and cementation Horizontal distribution and continuity of ground materials		Unequal settlement Energy requirements for excavation		Lunar water resources: permafrost

DEFINITION OF PROBLEM AREAS (CONTD)

LUNAR BASING (CONT'D)						
	I NATURAL SHELTER AVAILABILITY	II SUITABILITY OF POTENTIAL SITES				III LUNAR RESOURCES
RANK		A GEOLOGICAL ENVIRONMENT	B GEOPHYSICAL ENVIRONMENT	C ENGINEERING PROBLEMS AND REQUIREMENTS	D RADIOLOGICAL ENVIRONMENT	
6	Caldera or crater terraces Rilles	Vertical distribution and continuity of subsurface materials Presence of faults and fissures	Diurnal temperature wave	Optimize shielding properties of cover material Load-settlement relationships	Radiation shielding requirements	Lunar water resources: permeable tuff reservoir and near-surface ice deposits
5	Caldera lip fractures	Recent volcanism	Heat balance at lunar surface	Pressure distribution on underground structures Ground stabilization requirements (in situ and fill materials) Grading and fill requirements		Lunar water resources: deposits of obsidian, pitchstone, serpentine bodies, and zones of hydrated mineral
4		Recent faulting Presence of near-surface ice deposits	Thermal effect of rock blasting on ground materials			
3	Spatter cones		Foundation pressures due to frost heaving	Densification requirements		Lunar water resources: hydrothermally altered granodiorite (water-containing clay) Useful chemicals (volcanic sublimates)
2	Small meteor craters Undercut cliffs	Degree of weathering	Thermal effect on chemical stabilizing agents	Limiting unsupported slopes		
1	Large ejecta fragments		Seismic ground motion			Evidence of mineralization (intrusions, gossan, etc.)

DEFINITION OF PROBLEM AREAS (CONTD)

Problem Area: Origin, History, Age of Earth-Moon System

Fundamental Problems:

I. What is the geology of the lunar interior?

II. What is the geophysics of the lunar interior?

III. What are the radiologic characteristics of the lunar interior?

ORIGIN, HISTORY, AGE OF EARTH-MOON SYSTEM			
RANK	I GEOLOGY	II GEOPHYSICS	III RADIOLOGICAL
10			What is the age of the moon?
9	What is the nature of differentiation within the moon?	Does the moon have a core and a mantle?	
8	What is the nature of the major fracture patterns? Was the moon formed by cooling and solidification of a proto-earth? Was the moon formed by cold accretion, with or without later radioactive heating?	What is the thermal history of the moon?	
7	What is the variation of density with depth?	What is the internal composition of the moon? What are the geometric and gravimetric figures of the moon? What is the variation of density with depth?	What is the density and distribution of radioactive heat sources within the moon?
6		What is the thermal-mechanical-seismic energy budget of the moon? What is the extent of a lunar magnetic field?	
5	Why is there an apparent absence of transverse faulting? What is the nature of phase transformation within the moon?		
4	Was the moon formed by tidal rupture from the mantle of the earth?	Is the lunar magnetic field a dipole field, and where are its poles? What is the nature of the earthward bulge? What are the mechanisms that generate moon quakes? What is the tidal dissipation in and elasticity of the moon?	
3	What is the role of orbital capture in the origin of the moon?	What is the depth of focus, magnitude and frequency of moon quakes?	
2		How much of the magnetic field is induced and how much is the result of remnant magnetism?	
1		What is the extent of magnetically trapped charged particles (radiation belts)? What is the nature of convective transfer within the moon?	

DEFINITION OF PROBLEM AREAS (CONTD)

Problem Area: Origin, History, Age of Lunar Surface

Fundamental Problems:

I. What is the geology of the lunar surface?

II. What is the soil mechanics of the lunar surface?

III. What is the geophysics of the lunar surface?

IV. What are the radiologic characteristics of the lunar surface?

V. What is the nature of the lunar atmosphere?

ORIGIN, HISTORY, AGE OF LUNAR SURFACE					
RANK	I GEOLOGY	II SOIL MECHANICS	III GEOPHYSICS	IV RADIOLOGICAL	V ATMOSPHERIC
10	What is the petrographical composition of the bedrock and/or basement? What is the origin of surface features?				
9	What is the composition of surficial (rock) materials? Which craters are the result of meteor impact or collapsed calderas or domes?				
8	What is the mineralogical composition of the bedrock and/or basement? What tectonic processes and agents act on the lunar surface? What is the absolute age of the lunar surface?	What processes and agents are active in soil formation?	Is the lunar crust in isostatic equilibrium (do mountains have roots)? What is the subsurface structure of surface features (craters, rilles, terrae, maria, walled plains, etc.)? What are the structural differences between terrae and maria?		
7	What is the chemical composition of the bedrock and/or basement? What is the distribution of surface features? What is the relative age (stratigraphic, intrusive and paleontologic) of: structures? surface features?	What is the mineralogical composition of lunar soils?	What are the physical properties of the bedrock and/or basement?	Does residual radioactivity at the surface indicate a moon molten at any time?	Is "degassing" an active process on the moon or has it been?
6	What is the shape of surface features? What transportation and deposition processes and agents act on the lunar surface? What are the formations of surface features? What is the vertical and lateral continuity of the bedrock and/or basement? What is the vertical and lateral continuity of surficial materials? Where are zones of recent or incipient volcanism? What is the relative age (stratigraphic, intrusive and paleontologic) of formations?		What are the physical properties of subcrustal layers?		What is the composition of the lunar atmosphere and/or ionosphere?
5		What is the soil stratigraphy on the lunar surface?	What is the nature of the lunar diurnal temperature wave? What are the thermal equilibrium conditions at the surface? Where are the subsurface structures without surface expressions (intrusions, faults, domes, bubbles, etc.)?	Where are areas of abnormal radioactivity?	

DEFINITION OF PROBLEM AREAS (CONTD)

ORIGIN, HISTORY, AGE OF LUNAR SURFACE (CONT'D)					
RANK	I GEOLOGY	II SOIL MECHANICS	III GEOPHYSICS	IV RADIOLOGICAL	V ATMOSPHERIC
4	What weathering and erosion processes and agents act on the lunar surface?	What is the chemical composition of lunar soils?	What are the geothermal differences between terrea and maria? How does geothermal evidence confirm or modify other data related to the lunar surface?	How does particulate (protons, electrons, etc.) radiation act as a surface molding agent? To what extent are darkened areas of the lunar surface the result of radiologic bombardment?	What is the extent of a lunar atmosphere?
3	How can meteroids be distinguished from debris of lunar origin?	What is the rate of soil development?		What is the contribution of radiation to lunar albedo?	
2	What is the origin of tektites?	What is the composition of lunar soil gases?	What is the distribution of the moon's seismicity? What is the balance of particulate matter incident on the lunar surface and ejected from it?	What is the nature of fluorescence of the lunar surface? How much does radiation contribute to the chemical reactivity of the lunar surface?	
1	What life forms have existed and been preserved in rocks?				What is the extent of a lunar ionosphere?

APPENDIX C

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS

APPENDIX C

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS

This appendix is a tabulation of measurements and experiments that might possibly be made on the moon or on samples, photographs or technical data acquired during initial lunar explorations. Each discipline-based study group prepared a tabulation of this type at the beginning of the study to provide a starting point for determining instrument requirements.

Measurements and experiments were subjectively rated (10--most useful; 1--least useful) on the basis of their probable usefulness in five problem areas, i.e., hazard to the astronaut; trafficability; lunar basing; origin, history and age of lunar surface features; and origin, history and age of the earth-moon system. Notations were made concerning whether the measurement or experiment best could be made (a) on the moon with inplace material, (b) on the moon with samples, photographs or other technical data and (c) on samples, photographs or data returned to earth. Comments were made regarding such factors as need for a drill hole, possibility of significant areal- or time-dependent variations in the measurement, special energy sources required, need for incorporation in a Scientific Instrumentation Package (SIP) to permit data transmission to earth after astronaut departure, and the destructive or nondestructive nature of the test.

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Field Geology

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
ROCK PROPERTIES CLASSIFICATION									D = Destructive sample tests
Radioactivity	6	2	8	10	10	x		x	Areal variations
Mineral identification	2	7	9	10	10	x	x	x	
Rock composition	2	8	9	10	10	x	x	x	Areal variations
Apparent specific gravity	6	10	9	9	9			x D	
Per cent porosity	6	10	9	9	9		x	x	
Scleroscope hardness	2	7	7	4	4			x D	
Abrasive hardness	2	4	8	4	4			x D	
Specific damping capacity	2	2	5	1	1			x	
Modulus of rigidity	2	5	5	9	9			x	
Modulus of rupture	2	5	9	9	9			x	
Modulus of elasticity	2	5	5	8	8			x	
Compressive strength	10	10	10	8	8			x D	
Impact toughness	10	10	10	7	8			x D	
Longitudinal velocity	2	5	7	9	9			x	
Tensile strength	5	7	7	9	9			x D	
Poisson's ratio	2	5	7	9	9			x	
Permeability	2	2	4	5	5			x	
Texture: Grain size	6	6	6	8	8	x	x	x	Rough determinations on moon
Texture: Grain shape	6	6	6	8	8	x	x	x	Rough determinations on moon
Texture: Proportion of Glass to XL	4	4	4	8	7	x	x	x	Rough determinations on moon
Fabric: Grain arrang.	6	6	6	8	7	x	x	x	Rough determinations on moon
Fabric: Grain dist.	6	6	7	8	8	x	x	x	Rough determinations on moon
Rock color	4	4	4	2	2	x	x	x	Areal variations; precise determination on earth
Special features: Phase transformation	2	2	9	10	9		x	x D	Most probably done on earth; small crystals
Reflectivity	5	5	7	2	2	x	x	x	
Emissivity	7	2	7	2	2	x	x	x	
DUST PARAMETERS									
Classification and distribution	6	6	6	7	7	x	x	x	Photographic study on earth
Source	2	6	6	9	9	x	x	x	
Physiography of deposits	10	10	10	7	6	x	x		Photographic study on earth
Relief	10	10	10	4	4	x	x	x	Photographic study on earth
Slope	10	10	10	2	2	x	x		Photographic study on earth
Moisture	2	6	9	4	4			x D	Areal variations
Grain size	4	9	2	8	7	x	x	x	
Weathering	5	2	2	8	7	x	x	x	Areal and time variation

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Field Geology (Cont'd)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
Penetrability	10	10	10	8	8	x	x	x	
Chemical constituents	4	7	9	10	10	x		x D	
Thickness	10	10	10	8	7	x	x		Areal variation
Boundaries (lower horizon)	9	10	10	8	7	x	x		Areal variation
Color	2	2	2	2	2	x	x	x	Areal variation
Texture (size)	10	10	10	8	6	x	x	x	Areal variation
Structure	9	9	10	8	6	x	x	x	Areal variation
Consistency	9	10	9	4	4	x	x	x	Areal variation
Reaction	2	2	2	4	4			x	Areal variation
Special features	0	0	0	9	9	x	x	x	Micrometeoroid fragments, shatter cones, impactite.
Selenomorphology, tectonics, attitudes & trends	7	8	9	10	8	x	x	x	Mapping on moon; photointerpretation on earth; areal variation
Geologic age & stratigraphic position	4	2	2	10	9	x	x	x	Areal variation; mapping on moon; photointerpretation on earth
Stratigraphic (longitudinal X-sections)	2	2	5	10	9	x	x	x	Mapping on moon; photointerpretation on earth
Structures, kind, attitude	2	7	7	9	9	x	x	x	Areal variation; mapping on moon; photointerpretation on earth
Formational and intrusive contacts	0	1	2	8	9	x	x	x	Areal variation; mapping on moon; photointerpretation on earth
Bedrock structures, layering, jointing	4	7	7	7	8	x	x	x	Areal variation; mapping on moon; photointerpretation on earth
Refractive index of near surface gas	4	4	8	10	10	x	x	x	Areal variation
MINERALIZATION									
Attitude & extent of min. deposits	1	2	10	9	9	x	x	x	Lunar mapping, terrestrial photointerpretation
Kind & amount of ore minerals	1	2	10	9	9	x	x	x	Lunar mapping, terrestrial photointerpretation
Localization of ore & its genesis	3	5	9	9	9	x	x	x	Lunar mapping, terrestrial photointerpretation
Classification	1	0	0	0	0	x	x	x	Areal & time variation
Effect of thermal cycling	7	7	9	6	6	x	x	x	Areal & time variation
Radiation damage	4	2	9	7	6	x	x	x	Areal & time variation
Dust transport	6	8	9	7	6	x	x		Areal & time variation
Micrometeorite accretion	5	4	9	9	10				Field observation and descent photointerpretation
Sintering	5	8	8	8	8	x	x	x	Areal variations, time dependency
Vacuum outgassing	4	2	8	9	9	x	x		Active outgassing or evidence of past outgassing

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Field Geology (Cont'd)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
SAMPLING									
Surface	4	10	10	10	10	x	x		
Subsurface	4	10	10	10	10	x	x		
Orientation of samples	0	9	7	9	9	x	x		
Diamond	2	7	7	7	5			D	
Soil testing	2	7	7	7	7				
Power auger churn	2	7	7	2	2				
Percussion	2	7	7	2	2			D	
LOCATION									
Selenographic latitude & longitude	9	9	10	10	9	x	x		
Magnetic declination	2	5	5	9	10	x	x		
Natural landmarks	9	9	9	9	9	x	x		
Distances to sampling points	9	9	10	10	10	x	x		
Azimuths to sampling points	9	9	10	10	10	x	x		
Distances to contacts	2	7	9	9	9	x	x		
Azimuths to contacts	2	7	9	9	9	x	x		
RETURNED SAMPLES									
Petrographic microscope	0	7	8	10	10			x	
Mineral separation	0	4	8	7	7			x	
Wet & dry tests	0	6	8	9	9			x	
Spectrographic tests	0	6	9	9	10			x D	
X-ray examination	0	6	8	9	9			x D	
Quantitative analysis	0	4	9	9	9			x D	
Microchemical tests	0	4	7	7	7			x D	
Staining techniques	0	4	6	7	6			x D	
Electron microscope	0	4	8	8	9			x	
Differential thermal analysis	0	7	8	8	7			x D	

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geomorphology

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA: ON MOON	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA: ON EARTH	
PROPERTIES								All ND except where noted	ND = Nondestructive sample tests
Petrology	2	4	10	10	10	x	x	x	Rough determinations in place - areal variations
Shape and mass	2	2	5	5	10	x		x	Primarily analysis of orbital and descent photos
Vertical & stereo photography	10	10	10	10	10	x		x	Primarily analysis of orbital and descent photos
Oblique & ground photography	10	10	10	10	5	x			
Topographic (geologic) mapping	10	10	10	10	5	x		x	Field observation and orbital and descent photo analysis, areal variation
Slope	9	10	10	7	5	x			
Occurrence of steep slopes	9	10	8	5	5	x		x	Field observation and orbital and descent photo analysis, areal variation
Relief	8	10	8	8	5	x		x	Field observation and orbital and descent photo analysis, areal variation
Orientation of topographic high and lows	4	9	6	9	5	x		x	Field observation and orbital and descent photo analysis, areal variation
Areal occupancy of topographic high and lows	4	5	6	7	4	x		x	Field observation and orbital and descent photo analysis, areal variation
Planar shape of topographic high and lows	2	5	5	6	4	x		x	Field observation and orbital and descent photo analysis, areal variation
X-sectional shape of topographic high and lows	5	5	6	6	4	x		x	Field observation and orbital and descent photo analysis, areal variation
Grain size and shape	5	6	5	9	5	x	x	x	Sample examination, areal variations
Texture and mineralogic composition	5	5	9	9	10	x	x	x D	Sample examination, areal variations
Angle of repose	7	8	8	8	4	x		x	Areal variation with particle size
Degree of cementation	7	9	9	9	4	x	x	x	Study of samples on earth
Degree of cohesion	10	10	9	9	5	x	x	x	Study areal variations on earth
Porosity and permeability	2	2	8	7	7	x	x	x	Study of samples on earth, areal variations
Strength	9	10	10	2	2	x	x	x	Study of areal variations, sample study
Sorting or grading	2	7	7	7	2	x	x	x	Study of samples and photography
Lithology and stratigraphy	0	5	7	7	[illegible]	x	x		Study of areal variations
Density	5	8	8	2	2		x	x D	Primarily study of samples on earth

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geomorphology (continued)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
PROPERTIES (continued)									
Age	0	0	0	10	9			x	Age determinations on earth; areal variations
Reflectivity	5	5	7	2	2	x	x	x	Areal variations
Emissivity	5	2	6	2	2	x	x		
PHENOMENA									
								All ND	
Erosion	7	6	9	10	5	x			
Transportation	5	5	7	10	5	x		x	Mainly on moon, but checked on photos
Deposition	7	7	5	10	5	x		x	Mainly on moon, but checked on photos
Temperature	10	2	9	0	0	x			Requires SIP
Heat flow	5	0	9	8	10	x			Requires SIP areal variations
Radioactivity	7	0	9	7	10	x		x	Areal variations
Seismicity	5	2	5	9	10	x			Requires SIP, time and areal variations
Electrostatic forces	9	9	9	9	5	x			
Micrometeoroid flux	9	0	9	9	5	x			Requires SIP, observation, time variations
Meteoroid flux	9	0	9	10	5	x			
Solar radiation	9	0	9	9	5	x			Requires SIP, time and areal variations
Particle flux	8	0	9	9	5	x			Requires SIP, time and areal variations
Earth tides	2	0	2	7	9	x			Requires SIP, areal variations
Areal gradations	7	9	10	9	5	x		x	Study of orbital and descent photos
MICROMETEOROID ENVIRONMENT AND LUNAR EJECTA (ARTHUR D. LITTLE, INC.)									
Micrometeoroid flux	9	0	9	9	6	x			Requires development of instrument
Lunar ejecta flux	5	0	6	7	5	x			Requires development of instrument
Lunar ejecta momentum	5	0	5	3	1	x			Requires development of instrument
Lunar ejecta trajectory	1	0	3	2	1	x			Requires development of instrument

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Compositional Determination

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
ON SEPARATE MINERALS									
Magnetic mineral separation* Specific gravity mineral separation* Electrostatic mineral separation*	0	0	8	10	10			x D	Takes complex machinery
Differential thermal analysis	0	0	10	6	3			x D	
Gas chromatography	0	0	10	8	7			x D	
Gamma ray backscatter	0	2	1	0	0			x ND	Other density methods would be used on earth
Neutron backscatter	0	1	2	0	0			x ND	Other water determination methods would be used on earth
X-ray fluorescence spectrometry	0	0	8	8	9			x ND	
Infrared transmission spectrometry	0	0	8	7	6			x {ND-gas, D-solid}	
X-ray diffraction	0	7	9	10	10			x ND	
Mass spectrometry	0	0	9	9	10			x D	
UV-visible emission spectrometry	0	0	8	7	8			x D	
Gamma ray spectrometry	7	2	9	9	10			x ND	
Alpha ray spectrometry	3	0	3	8	9			x ND	
Alpha scattering spectrometry	0	0	1	1	1			x ND	Other methods are much better on earth-- returned samples
Neutron activation analysis	0	0	8	9	10			x ND	
ON BULK SAMPLES									
Mineral composition (solid)									All earth studies to be made on samples - "D" = destructive test; "ND" = nondestructive test.
(a) X-ray diffraction	0	7	9	10	10	x	x	x ND	More detailed study on earth
(b) Infrared spectrometry	0	0	8	7	6		x	x ND	More detailed study on earth
(c) Differential thermal analysis	0	0	10	6	3		x	x D	More detailed study on earth
Chemical composition (solid)									
X-ray spectrometry	0	0	8	8	9	x	x	x ND	More detailed study on earth
UV-visible spectrometry	0	0	8	7	8		x	x D	More detailed study on earth
Neutron act. analysis	0	0	8	9	10	x	x	x ND	More detailed study on earth
Alpha scattering spectrometry	0	0	7	6	6	x	x		
Neutron logging	0	6	8	3	3	x			Needs drill hole
Chemical composition (gas)									
Gas chromatography	5	2	10	8	7	x	x	x D	May require sample hole
Radioisotope composition									Age determination important
Gamma ray spectrometry	8	2	9	9	10	x		x ND	More detailed study on earth

*To be done on earth

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Compositional Determination (Cont'd)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
Alpha ray spectrometry	3	0	3	8	9	x		x ND	More detailed study on earth
Stable isotope composition									Age determination important
Mass spectrometry	4	2	9	9	10		x	x D	Samples on moon
Density measurement (solids)									
Gamma ray backscattering	0	8	7	3	3	x			
Lunar atmospheric pressure measurement									
Ionization gauge	6	2	8	5	0	x			
Detection of life forms									
Sample culture with pH readout	10	0	0	7	0		x	x D	More detailed study on earth
Sample culture with radio-isotope readout	8	8	0	6	0		x	x D	More detailed study on earth

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Radiological Experiments (Arthur D. Little, Inc.)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
Ultraviolet light	7	2	0	7	0	x			
Solar X-rays	7	2	2	7	0	x			
Solar wind	9	2	5	8	7	x			
Solar flares	10	2	10	6	6	x			
Magnetically trapped radiation	9	0	3	6	6				
Primary heavy cosmic rays	10	2	5	6	6	x			Measured before landing
Lunar radioactivity	7	2	7	6	6	x		x ND	
Secondary radiation	3	2	5	3	0	x			
Nighttime radiation	0	0	0	0	0	x			
Sputtered surfaces	3	7	6	6	6		x	x ND	
Chemical reactivity	8	8	7	6	6	x	x		
Cumulative radiative dose	9	3	8	6	6				
Total ionizing dose rate	9	3	8	6	6				Carried by astronaut
Particulate radiation flux	8	6	9	9	6				Measured before leaving LEM
Cosmic rays without magnetometer	5	2	5	6	6	x			
Cosmic rays with magnetometer	7	2	7	7	8	x			
Electron density	7	3	6	3	3	x			Requires SIP Instrument must be developed

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Group Study: Thermal (Arthur D. Little, Inc.)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
TEMPERATURES									
Landing gear	9	2	4	8	2	x			
Boot	8	2	4	4	2	x			
Surface	5	6	9	8	3	x			Requires SIP
Subsurface	2	1	9	9	3	x			Requires SIP
THERMAL CONDUCTIVITY									
Landing gear	2	7	8	7	3	x			
Subsurface	2	6	8	7	3	x			Requires SIP
THERMAL DIFFUSIVITY									
Surface	0	6	8	7	3	x			
Subsurface	0	6	8	7	3	x			
HEAT FLOW									
Surface	4	0	7	9	7	x			Requires SIP
Subsurface	0	0	6	10	8	x			Requires hole, SIP
Emittance	2	0	6	9	3	x			
INTERSTITIAL GAS PRESSURE									
Surface	4	0	7	8	6	x			Requires SIP
Subsurface	4	3	8	8	7	x			Requires hole, SIP

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geophysics

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
GRAVITY									"TD" = Technical data
Tidal	0	0	0	8	10	x			Requires SIP
Selenologic	4	4	6	9	9	x			Several points
Selenodetic	0	0	0	7	9	x			Requires transportation over large area
Deflection of vertical	0	0	0	9	9	x			Requires transportation over large area
SEISMIC-PASSIVE									
Noise									
Short-period	6	4	4	6	0	x			Requires SIP
Long-period	6	4	4	9	6	x			Requires SIP
Seismicity									
General	7	4	4	8	8	x			Requires SIP
Volcanic	6	6	8	9	9	x			Requires SIP
Tides	2	2	7	9	10	x			Requires SIP
Bombardments	7	2	6	9	9	x			Requires SIP
Acoustic impedance	2	2	6	9	9	x			Requires SIP
SEISMIC-ACTIVE (energy provided)									
Mechanical	2	4	4	6	4	x		x TD	Major interpretation of data on earth
Compressed gas	0	0	2	8	6	x		x TD	Major interpretation of data on earth
Chemical	0	0	0	9	9	x		x TD	Major interpretation of data on earth

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PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geophysics

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA: ON MOON	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA: ON EARTH	
MAGNETICS									"D" = Destructive sample testing
Properties:									"ND" Nondestructive sample test
Susceptibility: in situ	0	0	5	8	5	x			
of specimen	0	0	5	8	5			x ND	
Permeability: in situ	0	0	5	8	5	x			
of specimen	0	0	5	8	5			x ND	
Permanent magnetism	0	0	0	10	10			x ND	On samples
Induced magnetism	0	0	1	8	6	x		x ND	On samples
Total magnetic field	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Vertical component	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Horizonal component	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Vector sum & direction	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Total magnetic field gradient	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Vertical component gradient	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Horizontal component gradient	0	0	1	3	3	x			
at a plurality of points	0	0	1	8	8	x			
Phenomena:									
Paleomagnetism	0	0	0	8	10			x ND	On samples
Anisotropy	0	1	0	8	10			x ND	On samples
Diurnal variations (total field 1 point)	0	0	0	3	3	x			Requires SIP
at 2 or more points simultaneously	0	0	0	6	6	x			Requires SIP
Vertical component at 1 point	0	0	0	3	3	x			Requires SIP
at 2 or more points	0	0	0	6	6	x			Requires SIP
Horizontal component at 1 point	0	0	0	3	3	x			Requires SIP
at 2 or more points	0	0	0	6	6				
Secular variations (total field - 1 point)	0	0	0	3	3	x			Requires SIP
at plurality of points for horiz. and/or vert. components •	0	0	0	5	6	x			Requires SIP

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geophysics (continued)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
ELECTRICAL									
Properties (passive):									D = Destructive; "ND" = Non-destructive
Resistivity: in situ	0	8	4	8	6	x			
of specimen	0	4	2	4	3			x ND	
Conductivity: in situ	0	8	4	8	6	x			
of specimen	0	4	2	4	3			x ND	
Delectric: in situ									
of specimen	8	8	8	4	2	x		x ND	
Properties (active):									
Resistivity: in situ	0	8	4	8	3	x			Requires electrical current
of specimen	0	4	2	4	2			x ND	
Conductivity: in situ	0	8	4	8	3	x			Requires electrical current
of specimen	0	4	2	4	2			x ND	
Electrical transients: in situ	0	8	4	8	3	x			Requires SIP
of specimen	0	4	2	4	2			x ND	
Phenomena:									
Anisotropy	0	1	1	8	10			x ND	
Magnetotellurics	0	4	4	8	8	x			
Seismic-electrics	0	4	2	6	6	x			
Magnetohydrodynamics	10	0	10	0	0	x			
Correlation of E and H currents (short term one location)	0	1	6	5	5	x			
at a plurality of points	0	1	6	8	8	x			
Correlation of E & H currents (long term, one location)	0	1	6	5	5	x			Requires.SIP
at a plurality of points	0	1	6	8	8	x			Requires SIP
Electrostatics	8	8	8	4	2	x			
Thermal:									
Surface temperature	5	3	7	7	1	x			SIP measurement
Subsurface temperature	0	1	6	7	8	x			Requires hole
Vertical temperature gradient	1	1	6	7	8	x			SIP
Horizontal temperature grad.	3	1	1	0	0	x			
Heat flow	1	2	4	9	9	x			Requires hole, SIP
Specific heat (Cv)	0	1	2	5	3			x ND	
Specific heat (Cp)	0	1	2	5	3			x ND	
Thermal conductivity	1	2	4	7	7			x ND	
Thermal diffusivity	0	6	8	7	3			x ND	
Thermal inertia	0	1	4	6	5			x ND	
Coef. of linear therm. expan.	0	2	1	5	8			x ND	
Vol. coef. of therm. expan.	0	2	1	5	8			x ND	
Coef. of isothermal compr.	0	0	1	5	8			x ND	
Thermal shock resistance	1	3	4	9	4		x	x ??	

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Geophysics (continued)

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
Thermal: (continued)									
Thermal radiation (IR)									
Intensity	3	3	1	5	3	x			
Power density	0	0	0	5	3	x			
Wavelength	0	0	0	5	3	x			
Thermal well logging									
Temperature	0	0	3	4	4	x			Requires hole, SIP
Thermal conductivity	0	0	2	3	3	x			Requires hole, SIP
Geothermal survey	1	2	4	9	9	x			

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Soil Mechanics

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
Bulk density	8	7	8	5	2		x	x	Values measured on moon
Mineral or particle density	3	3	5	3	7			x	
Porosity or void ratio	6	5	6	6	3		x	x	Computed from above
Color	5	6	5	6	3	x		x	
Soil depth	9	9	10	9	2	x			
Penetration resistance	10	8	6	4	2	x			
Shear strength	7	8	9	3	1	x	x	x	In place, undisturbed & remolded measurements are all significant. Undisturbed sample most useful
Compressibility	4	5	8	2	1		x	x	
Bearing strength	7	10	10	2	1	x			
Structure (microstructures of soil)	3	3	7	10	3	x		x	
Stratigraphic elements	4	4	5	8	6	x			
Compaction	0	0	8	0	0		x	x	

PRELIMINARY MEASUREMENT AND EXPERIMENT EVALUATIONS (CONTD)

Study Group: Surveying, mapping, photography

MEASUREMENTS AND EXPERIMENTS	HAZARDS	TRAFFIC-ABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE		MEASUREMENT OR EXPERIMENT IS PERFORMED			COMMENTS
				LUNAR SURFACE	EARTH-MOON SYST.	IN PLACE	WITH SAMPLES, PHOTOGRAPHS, TECH. DATA		
							ON MOON	ON EARTH	
POSITION OF LEM									
Pilotage + D.R.	2	7	7	7	7		x		
Resection	3	3	3	3	3		x		
Nested photography during LEM descent	10	10	10	10	10		x	x	Verified by earth computations
POSITION & ELEVATION RELATIVE TO LEM OF:									
Geologic sample sites	1	6	9	9	9	x	x	x	Verified by earth computations
Soil mechanics sample sites	3	9	5	1	1	x	x	x	Verified by earth computations
Geophysical observation sites	0	5	6	7	7	x	x	x	Verified by earth computations
Geophysical observatory	5	0	0	0	0	x	x	x	Verified by earth computations
ORIENTATION OF:									
Radio antennae	3	0	3	2	1	x	x		
Rock samples	3	3	3	8	8	x	x	x	Verified by earth computations
Descent photographs	10	10	10	10	10	x	x	x	Verified by earth computations
DETERMINATION OF:									
Microrelief	2	9	3	3	3	x	x	x	Earth analysis of hand camera photos
Macrorelief	8	8	8	8	7	x		x	Earth analysis of descent camera photos
Surface particle size	2	8	8	3	3	x		x	Earth analysis of hand camera photos
Geologic attitudes	2	1	8	9	9	x	x	x	In place measurements + photo studies
								x	
Shape of moon	2	2	10	8	8			x	Not enough time, weight or volume available for in place determinations

APPENDIX D

INSTRUMENT EVALUATION SHEETS

APPENDIX D

INSTRUMENT EVALUATION SHEETS

Contained in this appendix are instrument evaluation sheets assembled by study groups. These comprise a comprehensive listing of instruments and equipment capable of making selected measurements--yielding data of scientific and technologic significance to identified fundamental lunar problem areas. The instruments and equipment listed herein include both state-of-the-art and those under development.

This compilation was not intended as a detailed specification of instrument or equipment performance and operating characteristics. Listed instruments or equipment were rated on a 1 to 5 scale under most column headings in the evaluation sheets. Table D-1 defines the rating scale for each column heading for which such a scale was used.

A few brief definitions follow which may facilitate interpretation of the information in the evaluation sheets:

- Instrument and Data Source - the name of the instrument or equipment and the information source from which data concerning same was taken. References, given by first author and year, can be found in full in a bibliography at the end of the appendix.
- Measurand - the physical property, quantity or condition being measured. In some cases, equipment use is listed.
- Operating Characteristics and Dynamic Range - performance specifications, such as accuracy, resolution, type of output signal, and the range of the measurand for which the instrument is useful.
- Reliability Rating - reliability rating, on a subjective basis, of the instrument's ability to perform its function under intended operating conditions. Not a measure of reliability for the APOLLO mission.
- Operating Time - operating time required to perform a measurement after setup - not necessarily the same as the time an operator's attention is required.
- Setup Time - time required to activate, calibrate and stabilize the instrument, and otherwise ready it to make a measurement. Where applicable, this includes sample preparation and insertion.

- Hazard Rating - where different, hazard to the astronaut is rated for both passive and active modes according to the scale in Table D-1 (e.g., 1-2).
- Number of people - required number of persons to perform a measurement with the instrument.
- Type Sample - NR: non-representative, R: representative, and U: undisturbed. Definitions for these three terms are given in Part II, Chapter IV.

A letter code, used to modify the ratings in order to further establish their accuracy, is also given in Table D-1. A listing of the extreme values reported for the lunar environment, given in Table D-2, will assist in evaluating an instrument's applicability for lunar use. These values were extracted from the final report on Radar Analysis of the Moon, Phase I, prepared by Texas Instruments Incorporated for Air Force Cambridge Research Laboratory, Cambridge, Mass., under Contract No. AF 19(628)-480.

TABLE D-1

RATING SYSTEM FOR INSTRUMENT EVALUATION SHEETS

SETUP, OPERATING TIME	RATING	RELIABILITY
0 - 5 Minutes	1	Very Reliable
5 - 15 Minutes	2	Reliable
15 - 30 Minutes	3	Fairly Reliable
30 - 60 Minutes	4	Poor
Over One Hour	5	Unreliable
HAZARDS-PASSIVE MODE First Rating		**HAZARDS-ACTIVE MODE** Second Rating
No known element of danger	1	No known element of danger
Some element of danger possible	2	Some element of danger possible.
A definite element of danger exists	3	Definite element of danger without shielding
Dangerous	4	Definite element of danger with shielding
Extremely dangerous	5	Extremely dangerous
STATE OF DEVELOPMENT		**LETTER CODE**
Lunar or space model	1	
Commercial available	2	E = Estimated
Prototype model	3	P = Postulated
Model in development ("breadboard") stage	4	U = Unknown
Undeveloped idea or concept	5	NA = Not Applicable

TABLE D-2

REPORTED EXTREMES OF SELECTED LUNAR ENVIRONMENTAL, SURFACE AND SHALLOW-SUBSURFACE FACTORS

	MOON
Particle Bombardment	10^{12} to 10^{8} protons/cm^2-sec
Atmospheric Density	$< 10^{10}$ molecules/cm^3
Atmospheric Pressure	0.076 to 10^{-16} mm Hg
Micrometeorite Flux Density	10^{-9} particles/cm^2-sec (> a few microns)
Magnetic Field	3000 to 2.5 gamma
Gravity	155 cm/sec^2
Temperature	
Surface	134° to -183° C
Near Surface	-23°C
Dust Thickness	0 to an average of 1 km
Dielectric Constant	2.7 to 1.1 ϵ_o
Thermal Conductivity	$< 10^{-4}$ to 5×10^{-6} calories/sec-cm-deg
Electrical Conductivity	4.8×10^{-4} to 3.4×10^{-4} mhos/m
Electrical Permeability	1.4 to ~1.0
Electron Density at Surface	10^3/m^3 to 10^7/cm^3
Surface Elements	Iron, Silicon, Magnesium, Aluminum, Oxygen, Potassium, Calcium, Neon, Nickel, Titanium
Glaciers	300 to 0 feet thick
Surface Charge	40 to 0 volts positive
Topographic Relief	
Small Scale	1.0 m to 0.1 mm
Large Scale	Up to 19,550 feet
Slopes	46 plus to 0 degrees

SHEET 1 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Field Geology

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Hand Lens Wards Nat. Sci. Estab. Geology Catalog	Optical properties	10X	0.6 E	0	1	1E	1E	1E	1	1	2	May need to be imprinted on astronaut's visor which is 3" from eye.
2 Sand-Measuring Comparator Wards Geology Catalog	Grain size	10X	0.25 E	0	4	U	1E	1E	1	1	2	
3 Cooke-MacArthur Petrographic Microscope Rank Organization England	Optical properties	10X to 100X	2 E	2 - 1.5 volts batteries for lamp	22.5	U	2	1E	1E	1	3	For petrography. Need to develop a cutting & grinding tool to make thin sections.
4 Microscope Talyden Corp.	"	25X to 100X	0.6 E	U (may require light source)	20	U	1	1	1E	1	2	
5 Hardness Points Wards Geology Catalog	Rock hardness	Range: 5,6,6.5, 7,7.5,8,9,10	0.3 E	NA	5	1E	1	1	1	1	2	
6 Streak Plate Wards Geology Catalog	Mineral identity	NA	0.13 E	NA	0.25	1	1	1	1	1	2	
7 Goniometer Wards Geology Catalog	Crystal interfacial angles	Mechanical scale readout, 1° accuracy	0.13 E	NA	2	1	1	1	1	1	2	
8 Pencil Magnet Wards Geology Catalog	Magnetic properties	NA	0.6 E	NA	1	1	1	1	1	1	2	
9 Charts, Comparison	Color, Grain size, Percentage estimate	NA	0.6 E	NA	4	NA	1	1	1	1	1	GSA Color chart AGI Data Sheets 1-13,15,16 and others (Percentage estimate, Grain size, etc.
10 Radar Refractometer	Atmospheric density	Cavity resonant freq., 1 kmcps	U	U	9	U	1E	1E	2	1	1	Ref: Air Force Cambridge Research Labs. AF Research Review 20 May 1963
11 Maps & Stereo or Monocular Photos	Location	1:25,000 scale Resolution: 85 ft. horizontal, 15 ft. vertical	0.06/ map E	NA	5/map E	U	U	1	NA	1	U	For landing site area.
12 Map or Stereo Holder Bookline, Inc.	NA	Magnifying single Prism stereoscope	2 E	NA	150	1	3	1	1	1	2	

SHEET 2 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Field Geology

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Plotting Instruments Keuffel & Esser Catalog	Scaled distance	NA	1	NA	6	1	NA	1	1	1	2	Dividers, scales, needles.
2 Alidade Keuffel & Esser Catalog No. 10	Sighted reference line	NA	5-7	NA	≃180	1	2	2 E	1	1	2	
3 Plane Table Keuffel & Esser Catalog No. 10	NA	NA	≃1	NA	113	1	NA	1	1	1	2	
4 Sun Compass	Azimuth relative to sun line	Accuracy: 2° E	3 E	NA	6	U	1	1	1	1	3	Requires sunlight. Modification would allow use as sun or earth compass.
5 Gyro Compass Astro-Space Laboratories	Azimuth relative to base line	Accuracy: 1°	3	Batteries 5w - 9v	22	U	1	1	1	1	3	Prototype developed by Astro-Space Laboratories Inc, Huntsville, Alabama.
6 Peep-Sight Alidade Keuffel & Esser Catalog No. 10	Azimuth	Accuracy: 2°	3 E	NA	6	1	2	1	1	1	3	
7 Brunton Compass William Ainsworth & Sons, Inc.	Azimuth, Dip angles	Accuracy: 2°	0.6	NA	9	1	1	1	1	1	2	May not be useful if lunar magnetic field is low. Combines sighting compass, prismatic compass, hand level, inclinometer.
8 Hinged Clinometer Keuffel & Esser Catalog No. 10	Dip angles	Accuracy: 2° E	0.6	NA	9	1	1	1	1	1	2	
9 Abney Level Keuffel & Esser Catalog No. 10	Slope, Dip angle	Bubble type; Accuracy: 3%	0.6	NA	18	1	1	1	1	1	2	
10 Hand Level Telescopic Keuffel & Esser Catalog No. 10	Slope, Dip angle	Bubble type	1	NA	13	1	1	1	1	1	2	
11 Telescope Field Model Questar	NA	6X to 10X needed	3 E	NA	10	1	1	1	1	1	2	Questar has 89 mm aperture, 56 in. focal length, 40-80X or 80-160X.
12 Jacob's Staff-Stadia Rod or Ranging Pole	Depth, Penetration resistance	Scale or markings to 0.1 ft	2 E	NA	9 collapsed	1	1	1	1	1	5	Uses: probe dust thickness, lend stability to astronaut; stadia rod or ranging pole. Possible accessory attachments: penetrometer, head for camera attachment.

SHEET 3 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Field Geology

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Tape Recorder Mod MTR-3100 Leach Corp.	Voice, Instrument data	2250'-3/4 in. Mylar tape. Tape speeds to 120 ips. Up to 14 channels record-reproduce	22	26 watts (24-32v dc unreg	262	1K	1	1	1	1	1	Various space models developed. Temp. range 0°F to 160°F. Hardened for vacuum radiation, particle impacts. Modification for Apollo mission probably desirable.
2 Crack Hammer Wards Geology Catalog	Sampling Tool	NA	2	NA	33	1	1 E	NA	4	1	2	
3 Rock Chisels Wards Geology Catalog	"	NA	2	NA	3	1	1	NA	4	1	2	
4 Casting Material	Micro-structure, Fossils	Quick hardening	U	NA	U	U	U	U	U	1	5	Must work in hard vacuum, low temperatures.
5 Entrenching Tools	NA		5 E	NA	180	1	1	NA	4	1	5	All purpose tool needs development. To assist in emplacement of scientific instrumentation package.
6 Watch, Chronometer	Time		0.5 E	NA	0.5	1	NA	NA	1	1	2	May need modification for lunar environment and mission requirements.
7 Stadia Reduction Tables Stadia Slide Rule Protractor, Keuffel & Esser Catalog 10	NA		0.4 E	NA	2	1	1	1	1	1	2	Surveying accessories.
8 Rock Cutting & Grinding Machine	NA		U	U	U	U	U	U	U	1	5	Sample preparation.
9 Micrometer Starrett Catalog	Thickness		0.4 E	NA	8	1	1	1	1	1	2	Slide thickness measurement.
10 Pedometer Keuffel & Esser Catalog No. 10	Distance		0.3	NA	9	U	1	1	1	1	2	Pace counter for surveying in absence of tracking equipment.
11 Konimeter (Dust examining microscope) W. Watson & Sons Ltd.	Grain size, Structure, etc.	216 X magnification	0.6	NA	36	U	1	1	1	1	2	Can assess dust particles of one micron; 1/2 micron are visible with dark ground lighting attachment.
12 Light Source (Flashlight)	Illumination	NA	1.7	batteries	- 12	1	1	1	1	1	3	For illumination in shadow areas. Needs development for operation in hard vacuum, reliability, ease of use by astronaut.

SHEET 1 OF 4

INSTRUMENT EVALUATION SHEET

STUDY GROUP Compositional

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Gas Chromatograph Wilhite (1963)	Compound composition	Analog voltage output, dyn. range: 10^4 Resolution: 10^{-10} moles	14	24 w-hrs/anal 15 w (avg.)	700	2 E	100 min/anal.	2 E	2	1	1	Determines 28 compounds, incl. CO, CO_2, NH_3, H_2O, O_2, N_2, organics. Surveyor Instrument. See also Donner (1963). Needs modification for Apollo.
2 Gas Chromatograph (Postulated For Apollo)	Compound composition	"	5 - 10 E	10 w avg. E 10 w-hrs/anal E	520 E	2	10 - 60 min	2 E	1-1	1	3	Apollo chromatograph could be more or less complex than Surveyor type.
3 X-Ray Diffractometer Weber (1963)	Relative compound composition	Output: voltage pulse count rate Dyn range: adequate Resolution: 5% of total mixture	21	60 w	800	2 E	4	2 E	1-2	1	1	Surveyor instrument. See also Project Surveyor Av. Week (3 July '61) and Phillips Defence and Space Lab Bulletin 1, No. 8. Reduced power, scintillation detector desirable for better sens.
4 X-Ray Spectrometer Weber (1963)	Elemental composition	Output: voltage pulse count rate Dyn. Range: adequate Resolution: 0.1%	30	25 w	800	2 E	3	2 E	1-2	1	1	Desirable modifications: (1) one or two non-dispersive channels for more information (2) scintillation detectors for better sensitivity and accuracy.
5 UV-Visible Absorption Spectrometer Beckman Inst.	Elemental composition	Output: analog voltage Dyn. range: $\approx 10^4$ Resolution: 10ppm for most elements	12	4 w	1730	3 E	2	2 E	1-2	1	1	Surveyor instrument. See also Project Surveyor, Aviation Week (3 July, '61)
6 Neutron Activation Analyzer Weber (1963)	Elemental composition	Output: voltage pulse count rate 96 channel pulse, ht. analyzer, Dyn. R: 10^3, Res: 0.1%	22	100	1700 E	U	3	2 E	1-2 E	1	3	Surveyor instrument development. See also ARS Journal, p. 631 (April, 1962). Needs 10^9 neutrons/cm^2-sec source.
7 Neutron Activation Analyzer (Postulated for Apollo)	Elemental composition	256 channel PHA	10-20 E	50-100 E	800 E	"	"	"	"	"	4	Development work in progress (Trombka 1963). 10^9 neutron/cm^2-sec source and 256 channel PHA needed for useful data.
8 Gamma Ray Spectrometer Weber (1963)	Radio-active isotopes	Output: voltage pulse count rate; 32 channel pulse height analyzer	12	<1.5 w	800	U	3	2 E	1 E	1	1	Ranger Block V instrument. Part of neutron activation analysis equipment.
9 Gamma Ray Spectrometer (Postulated for Apollo)	"	Output: voltage pulse count rate; 256 channel pulse height analyzer	10	<1.5 w	800	"	"	"	"	"	4	Desirable specs., thought possible.
10 Gamma Ray Backscattering Nuclear-Chicago	Density	Output: voltage pulse count rate Range: 2.0-7.5 gm/cm^3 Accu: $\pm$0.1gm/cm^3 below 2.0 gm/cm^3	Probe 20 Scaler 33	<1.5 w	Probe 520 E Scaler 720 E	U	1 E	1 E	1-1	1	2	NU-2 surface density probe, NU-1 portable scaler.
11 Gamma Ray Backscattering (Canup, 1962)	"	Output: voltage pulses, Linear range: 0.2 to 4g/cm^3 Accuracy: $\pm$0.1 g/cm^3 on consol. mat'ls.	Probe 3.2 Scaler 6 E	Probe: 0.01 w avg Peak: 9A @ 28v, 0.5 sec.	Probe 230 Scaler 520 E	U	1 E	1 E	1-1	1	3	Surveyor development instrument. See also JPL Space Programs Summary No. 37-17, Vol. VI, p. 42.
12 Alpha-Particle Scattering (Weber, 1963)	Elemental composition to AMU 40	Output from two 128 channel pulse height analyzers Resolution: $\leq$1 atom percent	6	1.4 w	250	3	1 E	2 E	2	1	3	Breadboard Model by Prof. Turkevich, Univ. of Chicago. See also JPL Space Programs Summary No. 37-20, Vol. I, (31 Mar. 1963) and Vol. VI, (30 April 1963).

SHEET 2 OF 4

INSTRUMENT EVALUATION SHEET

STUDY GROUP Compositional

INSTRUMENT AND DATA SOURCE	MEASURAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 UV-Visible (Weber, 1963)	Elemental composition	Output: Analog voltage.	2 E	1-3 w	50 E	U	U	U	U	1	3	Development prototype, Avco Corp. Performance probably similar to Beckman Surveyor instrument.
2 IR-Spectrometer (Weber, 1963)	Compound composition		2 E	1-3 w	50 E	U	U	U	U	1	3	Development prototype, Avco Corp. Primarily used for liquids, gases; recent work on analysis of minerals.
3 Sample Culture with Radio isotope Readout (Levin and Carriker, 1962)	Life form detection	Output: voltage pulse count rate Dynamic range: adequate. Accuracy: ±50-100 cpm (est.)	1.5	0.25 w	1600	2 E	1 E	NA (return trip)	2	1	1	"Gulliver" model developed for Mars life detection. Principle value in lunar program to detect possible dormant organisms hazardous on earth return. Possible radiation interference.
4 Sample Culture with pH Readout (Anon., C & E News 1964)	Life form detection	Output: 0-5v. D.C. Accuracy: ±0.2 pH units. Dynamic range: adequate	1.2	1.3 w	28	2 E	1 E	NA (return trip)	1	1	1	No interference from external radiation sources as in the above model.
5 Magnetron Ionization Gauge (Vanderslice, 1963)	Atmospheric pressure	Output: D.C. current. Dynamic range: 10^{-4} to 10^{-14} torr. Accuracy: adequate	8 E	15 E	85 E	2 E	1 E	1 E	1	1	3	Should be useful in locating any temporary atmosphere due to volcanism, to monitor contamination due to rocket exhaust gases. Space model of items 2, 3, on sheet 4.
6 Differential Thermal Analyzer (Gordon, 1960)	Mineral composition	Output: D.C. voltage change. Dynamic range: adequate. Accuracy: adequate	10 E	200 w E	860 E	2 E	3 E	2 E	2	1	3	Can be used for mineral composition. Best combined with gas chromatography for identification of thermal decomposition products.
7 Mass Spectrometer Consolidated Systems (Schrader, 1962)	Gas composition	Output: analog voltage, 0-5 v Dynamic range: 10^5 Resolution: 10^{-10} torr	20	27 w	700 w/electronics	1	1	1 E	1-2	1	1	Satellite instrument. Magnetic mass analyzer.
8 Mass Spectrometer (Brubaker, 1963)	All permanent gases, Organics to 50 AMU	Output: Analog voltage, 0-5 v Dynamic range: 10^6 Resolution: 10^{-12} torr	10-15	6 E	500 E	2	2 E	1 E	1-1	1	3	Could be quadrupole mass filter analyzer. Considered possible for Apollo (W.M. Brubaker, Consolidated Electrodynamics Corp., 1963) Scan 1-5 min.
9 Mass Spectrometer Very Desirable Specs.	Gas composition, Organics, Pressure	Output: analog voltage. Dynamic range: 10^6 Resolution: 10^{-14} torr	10-20	6 w E	<700 E	U	2	1	1-1	1	4	Highly desirable specifications. Could be quadrupole mass filter or time-of-flight instrument. Continuous or 1 sec. scan. Could determine all perm gases, organics to 500 AMU, pressure
10 Gas Chromatograph F&M Pyrolyzer Dual Column 720GC	Compound composition	Recorder output. Resolution: 10^{-8} moles	275	1200 w	10 ft^3	1	4	4	1	1	2	Commercial lab. instrument.
11 X-Ray Diffractometer Phillips	"	Dynamic range: 10^4 E	1400	4000 w	60 ft^3	1	5	2	2	1	2	Commercial lab instrument. Determine mineral composition, crystal structure.
12 X-Ray Spectrometer Phillips	Elemental composition	Recorder output. Dynamic range: 10^4 E Resolution: 0.01%	1400	4000 w	60 ft^3	1	3	2	2	1	2	Commercial lab instrument. All elements, Na to U.

SHEET 3 OF 4

INSTRUMENT EVALUATION SHEET

STUDY GROUP Compositional

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 IR Spectrometer Perkin-Elmer Model 21	Compound composition	Recorder output. Ranges: 2.5 to 18μ 4.0 to 40μ	270	650 w (Max.) 300 w (Aug.)	12 ft^3	1	3-4			1	2	Absorption measurement. Commercial lab instrument.
2 Carbon, Hydrogen, Nitrogen Analyzer F & M Model 180	C,H_2,N_2 content	Recorder output, Resolution: 0.1%	150 E	115v,15a	6 ft^3	1	2		1	1	2	Commercial lab instrument. Useful on any solid or liquid that burns at ≤1200° C.
3 Gas Chromatograph Aerograph Model 1520 Dual Column	Gases, Volatile compound composition	Recorder output, Resolution: 10 ppmE	250	1800 w	12 ft^3	1	3	4	1	1	2	Commercial lab instrument. Useful for compounds vaporizable at ≤400° C.
4 Gas Chromatograph Microtek 2500 R	"	Recorder output, Range: 10^8 Resolution: 10 ppmE	385	115v,20a	20 ft^3	1	3	4	1	1	1	Commercial lab instrument. Separates all vaporized compounds.
5 Thermoanalyzer Amimco Differential Thermal Analysis	Mineral composition	Recorder output. Differential temperature	200	10a,117v	8 ft^3	1	5	3	1	1	1	Commercial lab instrument. Identification of minerals by temperatures of exothermal and endothermal physical reactions.
6 f/6.3 Plane Grating Emission Spectograph Jarrell-Ash	Elemental composition	Photographic plate readout. Dynamic range: 10^6 Resolution: 0.1ppmE	580	1000 w E	46 ft^3	1	3	2	1	1	2	
7 Electron Probe Microanalyzer Norelco #12222	Elemental composition	Voltage pulses (scaler output) Resolution: 1% in spot area	900 E	20a,110v	96 ft^3	1	4	3	1	1	1	Commercial lab instrument. Qualitative and quantitative elemental composition of 1 micron spot, all elements Mg and above.
8 Nuclear Magnetic Resonance Varian A-60	Elemental and compound composition	Strip chart recorder output.	500 E	1000 w	15 ft^3	1	4	4	1	1	1	Commercial lab instrument.
9 Recording Spectrophotometer Bausch & Lomb Spectronic 505	Elemental Composition	Recorder output. Operating range: 200 - 800 mμ Resolution: ±0.5mμ (0.5%)	185	155v,5a	7 ft^3	1	3	2	1	1	1	Commercial lab instrument. UV, visible absorption spectra.
10 Recording Spectrophotometer Cary Model 15	Elemental composition	Recorder output, Operating range: 1850 - 8000 Å Resolution: 3Å (0.3%)	325	115v,5a	15 ft^3	1	3	2	1	1	1	"
11 Spectrophotometer Beckman DU	"	Analog meter readout. Oper. range: 200 - 800 mμ	160	550 w	2 ft^3	1	3	2	1	1	1	"
12 Recording Spectrophotometer Beckman DK	"	Recorder output. Operating range: 200 - 800 mμ	400 E	500 w	11 ft^3 E	1	3	2	1	1	1	Commercial lab instrument. UV, visible IR absorption spectra.

SHEET 4 OF 4

INSTRUMENT EVALUATION SHEET

STUDY GROUP Compositional

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Neutron Scattering (Johnson, 1962)	Amount hydrogen nuclei	Ra^{226}-Be neutron source, 5 decade scaler, spring-wound timer	Probe 45 Electronics 35	battery	Probe 250 Electronics U	2	2	2	2	1	2	Terrestrial field instrument, 5 millicurie source. Weight, volume include shielding.
2 Triggered Discharge Vacuum Gage, Model 22GT 210, General Electric	Atmospheric & pressure	Range: 10^{-4} - 10^{-14} torr, Output: 1v fullscale linear or log scale filament trigger	Gage: ~1 Elect: ~8	110 v 1 amp	Gage: ~8 Elect: ~1150	2	1	2	2	1	2	Capable of 450 °C bakeout. Warmup required w/log scale. Requires 2 kv power supply. Space hardened instrument in design stage.
3 Kreisman Vacuum Gage Model 1410 Vacuum Industries Inc.	"	Range: 10^{-4}-10^{-14} torr, Output: 2 amp/torr to 10^{-10} torr Ni^{63} trigger	Gage: 1.25 Elect. 27	8 w (4 kv, 2 ma)	Gage: 10 Elect: 1120	2	1	1	2	1	2	Developed under NASA Contract No. NAS 5-270.
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SHEET 1 OF 2

INSTRUMENT EVALUATION SHEET

STUDY GROUP Meteoroid and Radiological Measurements

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Survey Rate Meter JPL - Cal. Tech Neher, Anderson (1953)	Ionizing dose rate	Integrating ionization chamber. Range: 3.4×10^2 to 3.4×10^7 ion pairs/cm-sec of air. Protons: 10mev Electrons: 0.5 mev	1 E	0.1 w	70 E	1 E	1 E	1 E	1	1	1	Flown on Mariner II. Digital (pulse rate) output. Needs visual output meter for rate.
2 Portable Survey Rate Meter Rowland (1964)	"	Scintillator & photomult. tube 0-5 v dc analog rate output. Up 10^5 pulses/sec.	1.5	0.09 w 28 v dc	45 E	1 E	1 E	1 E	1	1	1	Flown on ATLAS. New design of item 4 for Gemini. Scaler memory can be integrated by 10 point commutator. Needs visual output rate meter. Set for 1 mev electrons.
3 Survey Meter Hoffman (1962)	Electron Proton flux	Scintillator phosphors on photomult. tubes. Electrons 5 to 200 kev, flux to 10^3 ergs/cm^2-sec-ster. Protons 0.1 to 10 mev, to 8×10^6 ergs/cm^2-sec-ster.	5.5	0.92 avg. 1.45 peak	224	1 E	1 E	1 E	1	1	1	Used on Explorer II, proposed for POGO. Analog 0-5 vdc output, also accumulator output 1 to 42,500 cps. Needs visual output meter.
4 Electron Spectrometer Reagan & Smith (1963)	Electron flux, energy	22 to 113 kev range, rates to 10^4/sec per tube Log rate output, 0-5 vdc	0	1.125 w	20 E	1 E	1 E	1 E	1	1	1	Uses 4 GM tubes and HV power supply. Used on several satellite flights. Visual indicating meter for 0-5 vdc needed.
5 Particle Spectrometer Fisher, et al (1963)	Proton, Electron flux, energy	Protons 10-100 Mev Electrons 0.05-1 Mev Binary coded output plus log rate (3 channels, 0-5 vdc)	11	2 w 28 vdc	200 E	1 E	1 E	1 E	1	1	1	Coded output, 16 channel pulse height analyzer. Improved design of this instrument for Gemini.
6 Particle Spectrometer Simpson (1964)	"	Range-energy loss telescope w/64 channel PHA, pulse rates to few hundred kcps.	7-8	1 w	475	U	1 E	1 E	1	1	U	Wedge shaped, 7" x 10" x 8 " deep. Digital output, 5 volt pulses.
7 Particle Spectrometer Van Allen (1963)	Electron, Proton flux, energy	GM tubes; 0.5 Mev. protons, 40 kev electrons	U	U	U	1 E	1 E	1 E	1	1	1	Now in orbit on IMP.
8 Personal Dosimeter Landsverk Electrometer Co., Beckman Inst. Co.	Integrated dose rate	Quartz fiber electrometer. 20 kev to 1400 kev, field scale range 0.2R to 50R, R.A.S. to 1000R	0.3 E	0 (charge to 180 v @ start of mission)	1	1	1	1	1	1	2	Shaped like fountain pen. 4 mr/day discharge rate. Optics must be modified for reading by astronaut. Needs sealing for vacuum environment.
9 Gamma-Ray Spectrometer (Weber, 1963)	Radio-active isotope	Output: voltage pulse count rate; 256 channel pulse height analyzer	12 E	1.5 w E	800 E	2 E	3 E	2 E	1	1	4	Ranger Block V instrument, part of neutron activation analysis instrumentation.
10 Nuclear Emulsion Plates	Particulate radiation	Ionization tracks produced in photographic emulsion	2 E inch shielding	0	10 E including shielding	1 E	1 E	1 E	1	1	1	Shielding needed for cislunar space travel; to be removed for exposure on lunar surface; then re-shielded for sample return-unexposed control plate should be retained in shielding case.
11 Electron Density Sensor Conceptual, A. D. Little	Electron density	Resonant cavity or system	U	U	U	U	U	U	1	1	5	Conceptual instruments: 1) Open-structured resonant cavity, characteristics function of change in diel. constant due to free electrons, or 2) shorted lecher wire system in static H field, emitted signal intensity ∝ electron density.
12 Chemical Reactivity Detectors	Reactivity with lunar surface material	Thermocouple output series millivoltmeter circuit; reference junction	0.5 E	.02 w E	17 E	1	2	1	1	1	3	Small samples of pressure suit and equipment materials, instrumented w/thermo-couple junction to measure temp. rise. Dropped to surface from LEM before egress.

SHEET 2 OF 2

INSTRUMENT EVALUATION SHEET

STUDY GROUP Meteoroid and Radiological Measurements

	INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1	Solar Plasma Spectrometer (Weber, 1963)	Flux, energy of charged particles	Output: analog voltage ∝ log current over 8 decades	10 E	<0.5 w	400 E	1	5	1	1	1	1	Two types: 1) Neugebauer electrostatic velocity selector; 2) Rossi probe. Estimates are for spectrometer-array set of 6. Both types developed for Ranger, Surveyor, satellites.
2	Meteoroid and Lunar Ejecta Detector	Flux, trajectory, momentum of particles	Four, four-stage counter outputs; voltages pulses from 3-channel microphone or displacement sens.	20 E	1 w E	1700 E	2	5	2	1	1	5	Conceptual instrument, proposed by A.D. Little. Two concentric hemispherical metallized dielectric sensing screens in sectors, backed by momentum absorber instrumented with 3 orthogonal displacement sensors.
3	Cosmic Dust Detector (Wyckoff, 1962)	Flux, momentum of dust particles	Flat, rectangular plate w/tuned Xtal microphone. Output from 2 binary counters	2 E	1 w E	U	1	5	2	1	1	1	Flown on Mariner II. Height of microphone output pulse proportional to momentum. One counter receives input from amplifier w/20 db less gain. Similar detectors flown on other satellites
4	Meteoroid-Ejecta Detector (Weber, 1963)	Flux, velocity, momentum of particles	Scaler or counter output, 2 channels plus pulse outputs from 2 acoustic detectors	11	0.4	1150	1	5	2	1	1	3	Dual array thin capacitor sheets backed by acoustic detector. Goddard SFC - J.L. Bohn, Temple Univ. Designed for Surveyor; capacitor sheets developed for EGO, POGO, Mariner B.
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INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Gravity and Seismics)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Portable Refraction-Reflection Seismograph Texas Instruments Explorer	Induced seismic motion	Output 0.5v or 0.5 ma, 5 - 200 cps freq. range, sensitivity 1 μ volt 120 db range	102	108 watts 9A @ 12 v	3630 w/o recorder	2	2	4	1	1	2	24 channel. Transistorized field instrument. Oper. temp. range -40° F to 140° F.
2 Portable Refraction-Reflection Seismograph Model 111 Geo Space Corp.	"	Output 0.3v or 0.5 ma, 5 - 300 cps freq. range, sensitivity 1 μ volt 80 db range	130 amplifier only	120 watts 10 amp @ 12 v	5180 amplifier	2	2	4	1	1	2	24 channel. Transistorized field instrument. Oper. temp. range -40° F to 140° F.
3 Portable Refraction-Reflection Seismograph Southwestern Industrial Electronics	"	2.5 to 100 cps freq. range, sensitivity 1 μ volt 60 db range	U	12 v	2930 amplifier w/power supply	2	2	4	1	1	2	12 channel. Transistorized field instrument. Oper. temp. range 0° F to 130° F.
4 Portable Refraction-Reflection Seismograph Model P-33, S.I.E.	"	4 - 600 cps freq. range, sensitivity 1 μ volt, 106 db range	105 w/o recorder	444 watts 37A @ 12 v	4500 w/o recorder	2	2	4	1	1	2	24 channel. Tube-type field system. Oper. temp. range 0° F to 130° F.
5 Portable Refraction-Reflection Seismograph Model M4E-12 Electro-Tech.	"	Output 0.2 mw into 50 ohms, 12 - 300 cps freq. range, sensitivity 1 μ v. 60 db range	43 amplifiers only	120 watts 12 v @ 10 amp	1260	2	2	4	1	1	2	12 channel. Tube-type field system. Oper. temp. range 0° F to 130° F.
6 Portable Refraction-Reflection Seismograph Model 1-44, United Geophysical Corp.	"	Dual output, 1 - 70 cps freq. range, sensitivity 1μ v. 88 db range	38 amplifiers only	44 watts 24 v	1420	2	2	4	1	1	2	12 channel. Tube-type field system. Oper. temp. range 0° F to 130° F.
7 Portable Shallow Refraction Seismic Timer Model 117, Geophysical Inst. Supply Co.	"	U	12	Self-powered	539	3	2	3	1	1	2	Single channel. Transistorized system. Oper. temp. range 0° F to 130° F.
8 Portable Refraction-Reflection Seismograph Model PT 100, S.I.E.	"	Output 0.15 v or 1.0 v rms, 3 - 500 cps freq. range, sensitivity 1μ v. 60 db range	amplifier: 100 lbs	96 watts 12 v @ 8 amp.	amplifier: 4700	2	2	4	1	1	2	24 channel. Transistorized field system. Oper. temp. range 0° F to 130° F.
9 Vertical Short Period Seismometer, Calif. Inst. of Tech., JPL Tech. Rep.#32-328	Natural lunar seismic noise	0.8μ v/millimicron @ 1 cps, 0.05 to 5 cps freq. range 30 db range	8E	1 watt	86	1	1	1	1	1	1	RANGER Seismic experiment instrument.
10 Vertical Short Period Seismometer, Lamont Geophys. Lab.	Natural lunar seismic noise	1.25 mv/millimicron 0.05 to 10 cps freq range, 30 db range (compressed to 20 db)	8E	0.3 watts E	100 E	1	5	1	1	1	1	Part of SURVEYOR seismic instrument, separable from rest of instrument with minimal redesign (Contract No. NASw-82)
11 3-Component Long Period Seismometer, California Inst. of Tech.	Moon-quakes	0.8μ v/millimicron @ 1 cps, 0.01 to 5 cps freq. range, 30 db range	10E	1 watt	600 in^3	U	5	1	1	1	1	Prototype developed and tested.
12 3-Component Long Period Seismometer, ITT-Lamont Geophys. Lab.	Moon-quakes	0.25 mv/millimicron 0.016 to 10 cps freq. range, 30 db range (compressed to 20 db)	32E	0.6 watts E	1400 E	1	5	1	1	1	1	Prototype SURVEYOR seismic instrument. Feedback loop output gives tidal gravity information. 2 watt peak heater may be required for thermal control. (Contract No. NASw-82)

SHEET 2 OF 2

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Gravity and Seismics)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Quartz Gravity Meter Texas Instruments Inc.	Gravity (milli-gals)	Optical null, dial readout, Range: 12000 mgal Resolution: ±0.01 mgal	6	<1 w	430	2	1	1	1	1	2	No temperature control.
2 La Coste & Romberg Gravity Meter	"	Optical null, dial readout, Range: 12000 mgal Resolution: ±0.01 mgal	30	3 w	1730	1	1	1	1	1	2	Metal spring temperature control.
3 Jakosky Pendulum Gravity Meter	"	Frequency or period output, Range: infinite, Resolution: ±0.1 mgal	30	2 w	1730	1	5	2	1	1	2	
4 La Coste & Romberg Tidal Gravimeter	"	Electro-optic null, Recorder output Range: 1000 mgal Resolution: ±0.001 mgal	100	30 w	7000	1	5	3	1	1	2	
5 Jakosky Torsion Balance	Gravity gradient	Optical scale read-out, Range: 100 Eötvös, Resolution: ± 1.0 Eötvös	50	1 w	7000	1	5	1	1	1	2	
6 Vertical Gradiometer Texas Instruments	"	Optical scale or optical null w/dial readout, Range: 80 - 200 Eötvös Resolution: ±1.0 Eötvös	5	1 w	430	U	2	1	1	1	3	Developmental model
7 Lunar Quartz Gravity Meter Texas Instruments	Gravity (milli-gals)	Electronic null, dial readout Range: 1000 mgal Resolution: ± 0.01 mgal	15	6 w	1300	U	1	1	1	1	4	Proposed development.
8 Tidal Gravity Meter	Induced earth (milligals)	Electronic null, analog voltage out-put. Range: 1000 mgal, Resolution: .001 mgal	33 E	1 E	1900 E	1	5	1	1	1	5	Proposed development; adaptation of LaCoste & Romberg tidal gravimeter.
9 Portable Refraction Seismic System (Kovach, et al., 1963)	Induced earth motion	Analog output voltage, Range: 20 db, Resolution: 10 mμ, Freq. response: 10 - 100 cps E	12	12	600 E	1	1	3	2	1	3	Prototype for soft lander or astronaut use. Deploys explosive array or 2000 ft line. W-V of source not included.
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INSTRUMENT EVALUATION SHEET

SHEET 1 OF 3

STUDY GROUP Geophysics (Thermal)

INSTRUMENT AND DATA SOURCE	MEASURAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Thermocouple Lion (1959) Griffiths (1925) Bristol Co. P 1238A Leeds & Northup Co. EN-52	Temperature	Linear, d.c., voltage generated by two dissimilar metal junctions at diff. temp. -200°C-+1000°C	0.05 to 0.25 P	10^{-3} w E	1 to 10 P	2 E	1 E	1 E	1 E - 1 E	1	2	Requires potentiometer or millivoltmeter for readout and reference junction at constant temp. Accuracy is 0.05°C to 0.1°C.
2 Resistance wire thermometer, Lion (1959), Misener & Beck (1960), Rosemount 9612 & 9625	"	Linear increase resistance with temp. of a pure metal -270°C to + 1000°C	0.05 to 0.25 P	15 x 10^{-3} w E	1 to 10 P	1	3 E	1 E	1 - 1	1	2	U. S. Patents 2,315,127; 2,375,892; 2,470,653; 2,245,700; 2,316,942; 2,395,192 Accuracy is 10^{-4} to 0.1°C. Requires resistance bridge.
3 Thermistor Lion (1959), Misener & Beck (1960) Fenwal Elect. EMC-5 Victory Engr.Corp.Catalog	"	Logarithmic resistance, decrease resistance w/temp. of semiconductive mat. -100°C - +300°C	7 to 40 E (2)	15 x10^{-3} w E	5000 to 7000 E (2)	2 E	1 E	1 E	1 - 1	1	2	(1) Requires resistance bridge. Accurate to within $\pm$ 1.0°C. (2) Figures refer to terrestrial field equipment. Lunar devices estimated 0.05 to 0.25 lb and 1 to 5 in^3.
4 Radiation pyrometer Griffiths (1925)	"	Thermocouple or thermopile sensing element 0°F to 3400°F	2 to 20 E (2)	10^{-3} w P	10 to 2000 E (2)	3 E	1 E	1 E	1 E - 1 E	1	2	Eppley Lab., Inc. (1963), Barber-Colman DB 1213-1, Pyrometer Instr. Co. No. 176. Lunar devices estimated 0.03 to 0.25 lb and 2 to 20 in^3.
5 Radiation bolometer Lion (1959) U. S. Patent 2,414,792	"	Resistance wire or thermistor sensing element, resistance function of temp.	0.5 to 2 P	15 x10^{-3} w P	4 to 20 P	3 E	1 E	1 E	1 - 1	1	2	(1) Requires resistance bridge.
6 Optical pyrometer Griffiths (1925) Pyro. Instr. Co. No. 176	"	Visual comparison of image with calibrated filament 1400°F to 7700°F	3.5 to 25 E (1)	0.5 to 5 P	75 to 2000 E (1)	1 E	2 E	1 E	1 E - 2 E	1	2	(1) Lunar devices estimated 0.03 to 0.5 lb and 2 to 30 in^3.
7 Interferometer spectrometer JPL (1962)	"	Spectroscopic analysis of 2 beam interferometry and Fourier transformation	0.63 E	0.5 to 5 P	4 E	4 E	2 E	1 E	1 E - 1 E	-0-	1 E	SURVEYOR instrument. Accuracy is no better than $\pm$ 4°C.
8 Metal expansion thermometer, Weston I&E 09-100-E, Bristol Co.Bull.T840 US Patent 2,487,968	"	Linear expansion of metallic sensing element with temp. -184°C to +540°C	0.5 to 2 P	0.1 - 2 P	2 to 20 P	1 E	1 E	1 E	1 E - 1 E	1	2	Vibrating string modulator can be used to give digital readout - U. S. Patent 2,447,816.
9 Liquid or vapor expansion thermometer, Misener & Beck (1960), U.S. Patent 2,477,835	"	Linear expansion of liquid or increase of vapor pressure with temp. -200°C to +650°C	1 to 10 E	0.1 - 1 P	5 to 200 P	1 E	1 E	1 E	2 E - 1 E	1	2	Includes mercury and alcohol types. Accurate down to $\pm$ 0.01°C. Figures refer to industrial models. Lunar devices estimated 0.05 to 0.75 lb and 1 to 30 in^3.
10 Gas expansion thermometer Bristol Co. Bull. T840, U.S. Patent 2,315,840 (1)	"	a)Linear pressure with temperature for a constant vol. b)Golay cell (2) -125°F to +600°F	0.05 to 0.75 P	0.1 - 5 P	1 to 30 P	3 P	1 E	2 E	3 E - 1 E	1	2	(1) Bellows type well-logging device. (2) Focus radiant energy on expansive gas to produce variations in pressure - U. S. Patent 2,424,976.
11 Electrolytic thermometer Lion (1959)	"	a)Logarithmic decrease of resistance with temperature	17 E	10^{-3} P	850 E	4 E	1 P	2 P	2 E - 1 E	1	3 E	Accurate to within $\pm$ 1.0°C. Figures refer to terrestrial models. Lunar devices are likely to be in range 0.25 to 1 lb and 4 to 16 in^3.
12 Insulation resistance thermometer, U. S. Patent 2,318,601	"	Temperature dependence vapor resistivity	0.13 to 0.5 P	0.5 to 1 P	1 to 20 P	5 E	1 P	1 P	1 P - 1 P	1	5 E	Conductivity of hygroscopic insulation containing a constant quantity of moisture in vapor condition, between 2 wires at different D.C. potentials, is function of temperature.

SHEET 2 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Thermal)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Thermal Probe Misener & Beck (1960)	Thermal conductivity	Transient state, dT/dt $\propto$ therm cond. 10^{-6} to 1.0 watt/cm-^{o}C	0.13 to 10 K	0.01 to 100 w. K	0.25 to 200 K	1	1	1-2	1 - 1	1	3	(1) Accurate to within $\pm$ 10%. Range includes gas measurements.
2 Thermal Comparator Misener & Beck (1960)	"	Steady state, empirical calibration 10^{-3} to 0.1 watt/cm-^{o}C	~1 E	$\lesssim$10 w. E	~1 to 10 E	1	2	2 E	1 - 1	1	3	Empirically calibrated; theory not developed.
3 Source-Sink Absolute, Misener & Beck (1960), U. S. Patent 2,475,138 Schroder (1960)	"	Steady state 10^{-3} to 0.1 watt/cm ^{o}C	~1 E	$\lesssim$ 10 w. E	~10 to 100 E	1	4	2 E	1 - 1	1	2	Requires careful technique for accuracy Therm. cond.= $\frac{dQ}{dt}\frac{(\text{thickness})}{\Delta T}$
4 Divided Bar Comparison Misener & Beck (1960) U. S. Patent 2,484,736	"	Steady state 10^{-3} to 0.1 watt/cm ^{o}C	~1 E	$\lesssim$ 10 w. E	~10 to 100 E	1	4	2 E	1 - 1	1	3	Ratio of thermal conductivity to standard is proportional to ratio of temperature drops. (1) Requires accurate standard for accuracy.
5 Thermal Logging Dobrin (1952)	Temperature	Various sensors record temperature as function of depth - 20 to + 200 ^{o}C.	5 to 250 E	10 to 500 P	20 to 400 E	2	4 E	3 E	2 E - 2 E	1 - 2	2	See also U. S. Patents 2,366,694; 2,480,720; 2,242,161; 2,383,455; 2,590,982; 2,313,384; 2,412,575
6 Thermal Logging	Thermal conductivity	Various sensors record changes of temperature at fixed intervals in a hole, 10^{-3} to 0.1 watt/cm-^{o}C.	5 to 250 E	10 to 500 w.P	20 to 400 E	3 P	4 E	3 E	2 E - 2 E	1 - 2	4	See U. S. Patents 2,290,075; 2,352,247; 2,242,612; 2,311,757; 2,414,862; 2,274,248; 2,342,827
7 Thermal Logging Dobrin (1952)	Vertical temperature gradient	a) Carefully spaced sensors record temperature difference as function of depth -20^{o}C to 200^{o}:	5 to 250 E	10 to 500 P	20 to 400 E	1 E	4 E	3 E	2 E - 2 E	1 - 2	2 E	U. S. Patent 2,301,326
8 Geothermal survey, Jakosky (1940) U. S. Patent 2,403,704	Temperature	Steady state temperature in shallow holes laid out on a grid -20^{o}C to +100^{o}C	15 to 25 P	1 w. E	5 to 50 P	1 E	5 E	3 E	1 E - 2 E	2	2 E	Accurate to within 0.01^{o}C.
9 Geothermal Survey Jakosky (1940)	Horizontal temperature gradient	"	15 to 25 P	1 w. E	5 to 50 P	2 E	5 E	3 E	1 E - 2 E	2	2 E	"
10 Thermal Conductivity Probe (Thermocouple) A.D. Little, Custom Scientific Inst.	Thermal conductivity, surface	Range: 2x10^{-6} to 1 watt/cm -^{o}C Output: dc millivolt analog signal	<0.5	10 mv to 1 w	5 E	1	4	1	1	1	2	Needs modification for lunar use. Measures rate of temperature rise due to heater in probe. Requires controlled temperature reference junction.
11 Thermal Conductivity Probe (Thermistor)	"	Range: 2x10^{-6} to 1 watt/cm - ^{o}C Output: analog voltage	<0.5	10 mv to 1 w	5 E	1	4	1	1	1	2	Resistance bridge, requires bias. Thermistor replaces thermocouple temp. sensor. Needs modification for lunar use.
12 Thermal Conductivity Probe (Thermocouple) A. D. Little	Thermal conductivity, diffusivity, subsurface	Range: 2x10^{-6} to 1 watt/cm - ^{o}C Output: dc millivolt analog signal	<0.5	10 mv to 1 w	5 E	1	5	3	1	1	3	Similar to 10, but requires installation in borehole or deep insertion in dust or soil. Needs development.

INSTRUMENT EVALUATION SHEET

SHEET 3 OF 3

STUDY GROUP Geophysics (Thermal)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Thermal Conductivity Probe (Thermistor)	Thermal conductivity, diffusivity, subsurface	Range: $2x10^{-6}$ to 1 watt/cm - °C Output: analog voltage	< 0.5	10 mw to 1 w	5 E	1	5	3	1	1	3	Similar to 11, p. 2; requires installation in borehole or deep insertion in dust or soil. Needs development.
2 Modified Flash Radiometer	Thermal diffusivity, surface	Range: $3x10^{-6}$ to 2 cm^2/sec Output: analog voltage, DC as f(t)	5 E	U	< 1700	U	5	3	1	1	5	Conceptual instrument. Progression of heat wave due to flashed radiation illum. (Xenon or laser source) monitored by IR detectors focused on surface.
3 Reflectance Radiometer UV-Visible-IR	Surface emittance, reflectance	Output: analog voltage, DC	5 E	1 w E	100 E	U	5	2	1	1	5	Conceptual instrument. Radiation detectors monitor reflected and emitted radiation, probably using solar energy as source. Spectral info. in UV, visible & IR bands required.
4 Radiometric Heat Flow Meter A. D. Little	Heat flow surface	Range: 10^{-4} to 1 watt/cm^2 Output: analog voltage	<0.5	few mw	12 E	U	5	2	1	1	5	Conceptual instrument. Blackened disc suspended above undisturbed surface, instrumented with thermocouples for temperature, ΔT.
5 Heat Flow Meter (Modified) National Inst. Labs Beckman-Whitley	"	Range: 10^{-4} to 1 watt/cm^2 Output: analog voltage	1 E	few mw	12 E	U	5	2	1	1	5	Conceptual instrument. Conductive type requires surface emplacement with minimal disturbance. Thermocouple or resistance thermometer sensors.
6 Line Source Pressure Gauge A. D. Little	Interstitial gas pressure	Range: 10^{-4} to 100 torr (several sensors for span) Output: DC voltage	1.5 E	0.1 w E	15 E	U	5	3 or 4	1	1	3	Modification of existing probe required. Surface or subsurface, latter requires borehole. Measures therm. cond. of reference powder sample in pressure equil. w/surface material.
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SHEET 1 OF 2

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Magnetics)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Fluxgate Magnetometer Gulf Oil Corp.	Total magnetic field	± 1 γ resolution	75	A.C.	3200	2	1	2	1	1	2	
2 Fluxgate Magnetometer Sharpe-Litton	"	Range: 1000 - 100,000 γ	9	12 "D" cells	448	4	1	2	1	1	2	
3 Proton Precession Magnetometer, X-4940 X-4942, Varian Associates	"	Range: 1 to 12000 or 52000 γ Resolution: (X-4940), 2 γ (X-4942) 0.6 γ	X-4940: 6 X-4942: 2.7	Batteries	X-4940: 136 X-4942: 92	2	1	1	1	1	2	Requires bias field of about 5000 γ.
4 Rubidium Vapor Magnetometer Model V4938 Varian Associates	"	Range: 6100 γ Resolution: ±0.01 γ	86	110 v. ac 25 v. dc	2853	2	1	1	1	1	2	
5 Low Field Helium Magnetometer Texas Instruments	Total field plus 3 components	Range: ± 364 γ Resolution: 0.5 γ (1cps pass band)	6.15	7.0 w	257	U	1	1	1	1	1	Flight model designed & built for JPL. (Contract No. 950355). Oper. temp. range: -55°C to +55°C (sensor). -20°C to +65°C (electronics)
6 Search Coil Magnetometer Space Technology Labs.	Magnetic field	Range: 15,000 γ Resolution: 1 γ	3	U	24	2	1	1	1	1	1	Flown on Pioneer I & II.
7 Schmidt Type Balance Askania	Magnetic field, vertical component	60,000 γ range Accuracy: ± 2 γ	23 w/tripod	0	2400 w/tripod	2	1	1	1	1	2	Photoelectric recording unit available if desired (30 lbs, 1000 in^3 w/tripod).
8 Schmidt Type Balance Ruska	"	1000 - 2000 γ	"	0	"	2	1	1	1	1	2	
9 Schmidt Type Balance Hilger-Watts	"	1000 - 2000 γ	"	0	"	2	1	1	1	1	2	
10 Torsion Fiber Balance Askania Type: Micro Gfz	"	Range: 60,000 γ Accuracy: ± 2 γ	7.50 w/tripod	0	200 w/tripod	2	1	1	1	1	2	
11 Schmidt Type Balance Askania	Magnetic field, horizontal component	Range: 40,000 γ Accuracy: ± 2 γ	23 w/tripod	0	1720	2	1	1	1	1	2	Photo-electric recording equipment available. See vertical component instrument.
12 Schmidt Type Balance Hilger-Watts	"	Range: 2000 γ	"	0	U	2	1	1	1	1	2	

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Magnetics)

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Schmidt Type Balance Ruska	Magnetic field, horizontal component	40,000 γ accuracy $\pm 2\gamma$	23 w/tripod	0	1720	2	1	1	1	1	2	
2 Torsion Fiber Balance Type Gfh Askania	"	Range: 40,010 γ Accuracy: ± 2 γ	18.8 w/tripod	0	1720	2	1	1	1	1	2	
3 Earth Inductor 2-Coil Type (Roman & Sermon, 1934)	Magnetic field gradient	Resolution: 0.2%	25	2 dry cells	17,800	3	2	2	1	2	2	
4 Rubidium Vapor Model V 4938G Varian	"	Resolution: 0.2 ppm	U	U	U	2	1	1	1	1	2	
5 Compass	"		0.25	0	4	1	1	1	1	1	2	
6 Dip Needle "Super Dip" Gisco-Sharpe D-2	Magnetic inclination		2.5	0	24	1	1	1	1	1	2	
7 Earth Inductor C. I. W.	"	Inclination angle Resolution: 0.1'	35	Batteries	144	2	1	1	1	1	2	
8 Mooney Type Bridge Gisco MS-3	Magnetic susceptibility (surface)	Range: 100,000 x 10^{-6} cgs Resolution: 2×10^{-6}	12 w/o batteries	U	1152	2	1	1	1	1	2	In situ measurement.
9 Modified Mooney-Type Susceptibility Bridge JPL	"	Range: 100,000 $\times10^{-6}$ cgs Resolution: 2×10^{-6}	0.6	0.06 w	17	2	1	1	1	1	1	Bollin, E. M. (1962) Camup, et al. (1962) Surveyor surface instruments; in situ measurement.
10 "	Magnetic susceptibility (subsurface)	U	U	U	U	U			1	1	3	Surveyor subsurface instrument Bollin (1962). Designed for small borehole. Needs additional development.
11 Inductive Bridge-Bore Hole Instrument Socony Mobile	"	Resolution: 1×10^{-6} cgs	U	U	U	2	3	2	1	1	1	Broding et. al. (1952), Geophysics, Vol. 17, No. 1, p. 1.
12 Fluxgate Magnetometer (Wyckoff, 1962)	Magnetic field, total + 3 components	2 Ranges: 0 to $\pm64\gamma$, 0 to $\pm320\gamma$. Noise equiv.: 0.25γ. Resolution, low range: 0.6γ.	4.6	6	U	1	1	2 B	1	1	1	Flown on Mariner II. Coils available to counteract permanent or induced field of spacecraft up to 100 gamma.

SHEET 1 OF 1

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysics (Electrical)

	INSTRUMENT AND DATA SOURCE	MEASURAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1	Gish-Rooney (4 Electrode Spread) Gisco 2647	Resistivity (AC, DC, active or passive)	Square wave current source, Slidewire potentiometer Accuracy: 0.5%	15 w/o batteries	200 w E	3460 w/o probes	2	2	3	1	1-2	2	Terrestrial vacuum tube instrument. Needs modification and miniaturization. Data can be used to calculate dielectric constant, conductivity.
2	Self Potential-Resistivity Equipment Gisco SP 56	plus spontaneous polarization	DC power supply, vacuum tube volt meter, resistors, 4 electrodes & 4 reels of wire	48 w/o batteries	200 w E	1080 w/o probes	2	2	3	1		2	"
3	Four Electrodes, Voltmeter, Cables, AC DC, Pulse Current Source		Similar to 2, with AC DC, pulse power supply	14 E	200 w E	380 E	2	2	3	1	1	3	Estimates for needed modification of 2 for lunar use.
4	Self-Potential Unit Gisco VP 6	Spontaneous polarization	Range 250 1000 mv	14 w/o batteries	0	722 w/four-probes	3	2	2	1	1	2	Terrestrial vacuum tube instrument. Needs modification and miniaturization.
5	Two Electrodes, Voltmeter, Cables		Range 1000 mv	10 E	battery powered	300 E	2	2	3	1	1	3	Electrodes, cables and voltmeter from 1, 2 or 3 could be used. Estimates for lunar model; modification of terrestrial types needed.
6	Probe Dielectrometer Model 611 A Microwave Instruments Co.	Dielectric constant, loss tangent	Diel. const. range 1 - 50 Loss tang. range: 0.001 - 3.2 Accuracy: ~4%	140	350 w	11,000 E	2	1	1	1	1	2	XY recorder output. Operating frequency 8.6 kmcps. Measurement area, 1 in. dia. flat surface. Lab or industrial type instrument.
7	Tuned Circuit Probe Dielectrometer Eimer (1963)	Relative permittivity	U	E	<1 w E	40 E	2 E	2	1	1	1	4	Capacitance change to retune circuit in parallel with plate placed near lunar material related to permittivity. Needs development, calibration with simulated lunar materials.
8	Charged Dust Detector Weber (1963)	Fluxes of charged particles	Electrostatic velocity selector; qualitative	2 E	<0.5 w E	60 E	3 E	1	2	1	1	4	Based on Neugebauer Solar Plasma Spectrometer. Cannot separate speed and charge/mass ratio. Measures particle fluxes in groups.
9	Cal-Tech Portable Refraction Seismograph, 2 Electrodes, Voltmeter, Cables	Seismic-electric effect	U	42	Battery powered	950	3	2	3	1	1 or 2	2	
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SHEET 1 OF 1

INSTRUMENT EVALUATION SHEET

STUDY GROUP Geophysical (Electric Logging)

INSTRUMENT AND DATA SOURCE	MEASURAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 SP Electrode Electro-Tech Labs. Keck Assoc., Inc. Schlumberger, Doc.8 Well Reconnaissance	Self potential	$\lesssim 10^2$ Ω-cm E formation fluid resistivity error $\gtrsim$ 10% E	15 E	None	200	2	Single datum: 1E Contin-uous record 1E	1 E	2E - 2E	1	2	NA lunar use--requires water-filled hole, formation fluids. Deduce resistivity of formation fluids, bed boundaries, "shaliness" of formations. 1 min/reading, 60'/min. See also Dakhnov (1962).
2 Single Pt. Device Electro-Tech Labs. Keck Assoc., Inc. Schlumberger, Doc.8 Well Reconnaissance	Resistiv-ity	$\lesssim 10^4$-10^5 Ω-cm E error $\gtrsim$10% E	15 E	50-1500	200	2	"	"	"	"	"	Not applicable to lunar use--requires fluid-filled borehole. See also Dakhnov (1962).
3 Normal Device Short & Long Electro-Tech Labs. Keck Assoc., Inc. Schlumberger, Doc.8 Well Reconnaissance	"	$\lesssim 10^4$-10^5 Ω-cm E error $\gtrsim$ 10% E	15-50	50-1500	200	2	"	"	"	"	"	Not applicable to lunar use--requires fluid-filled borehole. Weight depends on current, voltage electrode distance, 18 in. or 60 in. See also Dakhnov (1962).
4 Lateral Device Short & Long Electro-Tech Labs. Keck Assoc., Inc. Schlumberger, Doc.8 Well Reconnaissance	"	$<10^4$-10^5 Ω-cm E error $\gtrsim$ 10% E	15-50	1500	200	2	"	"	"	"		Not applicable to lunar use--requires fluid-filled borehole. Weight depends on distance of current electrode to mid-point of voltage electrodes. See also Dakhnov (1962).
5 Guard Electrode Device (Laterolog) Schlumberger, Document 8 Dakhnov (1962)	"	10^4-10^5 Ω-cm E error $\geq$10% E	15-50	1500	200	2	"	"	"	"	"	Not applicable to lunar use--requires fluid-filled borehole. Accuracy better than instruments 1, 2, 3, 4.
6 Micro-normal Device Schlumberger, Document 8 Dakhnov (1962)	"	10^4-10^5 Ω-cm E error$\gtrsim$ 10% E	10	1000	70	2	"	"	"	"	"	Not applicable to lunar use--requires mud cake.
7 Micro-inverse Device Schlumberger, Document 8 Dakhnov (1962)	"	10^4-10^5 Ω-cm E error $\gtrsim$10% E	10	1000 E	70	2	"	"	"	"	"	Not applicable to lunar use--requires mud cake.
8 Micro-laterolog Schlumberger, Document 8 Dakhnov (1962)	"	10^4-10^5 Ω-cm E error $\simeq$10% E	10	1000	70	2	"	"	"	"	"	Not applicable to lunar use--requires mud cake. Accuracy better than micro devices 6 & 7.
9 Induction Device JPL Schlumberger, Document 8 Dakhnov (1962)	"	10^{12}Ω-cm P error $\geq$10% E	5 P	500 P	70 E	2 E	"	"	"	"	1,2	Applicable to lunar use--no borehole fluid required. Dry rock $\simeq 10^{12}$ Ω-cm. Permafrost $\simeq 10^4$Ω-cm. W-P-V values for JPL-Bollin susceptibility-resistivity Surveyor instrument.
10 Scratcher Electrode Device Dakhnov (1962)	"	10^{12}Ω-cm P error $\gtrsim$10% E	0.6	0.01	18	3 E	"	"	"	"	3	Applicable to lunar use--direct contact achieved. Dry rock: $\sim 10^{12}$ Ω-cm, Permafrost: $\sim 10^4$Ω-cm. Accuracy depends on contact resistance.
11 Induced Polarization Device Dakhnov (1962)	Metal factor	U	5 P	<500 P	70 E	3	"	"	"	"	5	Applicable to lunar use of scratcher electrodes used. Measures degree of disseminated mineralization + water content.
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SHEET 1 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Soil Mechanics

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Pocket Penetrometer, CL-700 Soiltest, Inc.	Penetration resistance	0 - 4.5 kg/cm^2	0.26	0	5	2	1	1	1	1	2	Spring loaded, optical scale
2 Unconfined compression tester U-115 Soiltest, Inc.	Compressive strength	0-200 lb	25 lb (E)	0	U	2	2	3	1	1	2	Commercial laboratory instrument. Applicable to cohesive soils only.
3 Unconfined compression tester U-160 Soiltest, Inc.	Compressive strength	0 - 500 lb	32	0	1200 (E)	2	2	3	1	1	2	same as above (approx. 8 other unconfined compression test apparatus are shown in Soiltest catalog. These are the lightest and simplest)
4 Triaxial assembly T-114 Soiltest, Inc.	Confined compressive strength	0 - 800 lb. Strain control rate 0 - .5 in./min.	800	110V 60 cy var. pwr depending on load	160,000	1	variable	4	2	1	2	Commercial laboratory instrument. Requires additional instruments for sample preparation. Not suitable for lunar use.
5 Soil trafficability test set Army Tech bull. TB ENG 37	Cone index, Penetration resistance	0 - 150 lb. $\pm$ 1 lb.	19	0	1200 (E)	3	1	1	2	1	2	Data must be correlated with vehicle performance to be useful. Principally applicable to cohesive soils
6 Proving ring penetrometer Army Tech. Bull. TB ENG 37	Penetration resistance	0 - 150 lb. (limited by wt. of operator)	8 (E)	0	400 (E)	3	1	1	2	1	2	This is a major component of (5) above. May be useful in context other than trafficability, as device for qualitative comparison of soil bearing strength
7 Lunar Staff w/ proving Ring attachment	Penetration resistance	0 - 150 lb. (limited by wt. of operator)	2.5 (E)	0	20	3	1	1	2	1	2	Conceptual instrument designed for lunar use and compatibility with Apollo objectives
8 Split spoon sampler Terzaghi & Peck (1948)	Penetration resistance	Blow count to advance sample given distance (as index of penetration resistance)	NA	U	U	3	variable	4	2	2	NA	Test result is a by-product of percussion drilling or sounding, in which blow count to advance tool is logged and used to correlate soil consistency from hole to hole.
9 Surveyor penetration hardness device Thorman (1963)	Hardness of surface materials	Penetration resistance ranges: soil > 10 psi rock 4000 - 25,000 psi	U	< 1 w	U	3	1	1	1		1	Utilizes piezolectric accelerometer to produce deceleration-time curve for various materials. Modification needed to produce useful system for manned investigations.
10 Remolding apparatus Army Tech. Bull. TB ENG 37	Remolding index	Manually determines ratio of penetrometer readings in remolded soil to those in "undisturbed" soil	19	0	1200 (E)	3	1	1	2	1	2	Remolding index may be useful for evaluating suitability of soil as a construction material and for observing tendency of broken cohesive bonds to "heal."
11 Lunar overshoe Av. Wk. & Space Tech. 10/28/63	Bearing capacity	NA	U	NA	NA	3	NA	NA	1	1	1	This integral part of Apollo space suit will provide qualitative data on bearing capacity by means of the variable-size foot pads.
12 Gamma-ray backscattering Nuclear-Chicago	Density	Output: voltage & pulse count rate Range: 2.-7.5 g/cm^3 Accu: $\pm$ 0.1 g/cm^3 below 2.0 g/cm^3	55	1.5 w	1240 (E)	U	1	1	1	1	2	

INSTRUMENT EVALUATION SHEET

STUDY GROUP Soil Mechanics

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Gamma Ray back-scattering (Canup, 1962)	Density	Output: Voltage pulses, Linear Range: 0.2-6.8 g/cm^3 Accu: ± 0.1 g/cm^3 on consol. mtls.	9.2	Probe: .01 w avg Peak: 9A@28v, 0.5 sec.	750 (E)	U	1	1-1	1-1	1	3	Surveyor development instrument.
2 Known volume thin-wall density sample tube. (conceptual)	Volume	NA	0.5	0	15	1	1	1	1	1	3	Known volume of "undisturbed" sample which just fills tube to capacity will be used in conjunction with terrestrially determined weight to compute bulk density
3 Vane shear apparatus Soiltest, Inc.	Shear strength	0 - 600 lb torque	110	0	1200 (E)	U	2 (E)	2 (E)	1	1	2	Weight & volume depend on depth to be tested. Usually used in conjunction with drilling apparatus for making hole
4 Vane shear apparatus (conceptual)	Shear strength	0 - 200 lb torque	6 (E)	0	40	U	2 E	2 E	1	1	3	Proposed lunar design will limit depth to upper 2 feet & employ light weight materials.
5 Vane shear apparatus-lab model Soiltest, Inc.	Shear strength	0 - 5 in-lb	100	0	2300	U	2	2	1	1	2	Instrument has redesign potential for lunar field use.
6 Direct shear apparatus Soiltest, Inc.	Shear strength	0 - 1500 lb load applied through gear box by hand	200 lb (E)	0	7000 (E)	1	2	4	1	1	2	Estimated weight and volume include stand and weights for applying load. This is simplest commercially available laboratory direct shear apparatus.
7 Soil mechanics test apparatus (Thorman, 1963) with conceptual modifications	Shear strength & bearing capacity		23	250 w-hrs	900	U	3	1	1	1	3	Estimated weight, volume, power take into account modifications to convert Surveyor apparatus to manual operation as portable field test instrument, using screw augers or operator weight as load.
8 Cohron shear-graph (Cohron, 1963)	Shear strength	Normal stress to 20 psi; tangential stress to 8 psi; spring loaded	3	0	50 (E)	U	1	1	1	1	2	System needs careful evaluation with respect to reliability of data results.
9 ITT Direct shear Apparatus (Vey & Nelson, 1963) w/ conceptual modifications	Shear strength	Normal load applied by hanger weights; shear force applied through gear box & electric motor	U	U	300 (E)	U	2	3	1	1	3	System is a laboratory prototype, but is noted as possible pattern for lunar field model. Suggest constant force springs for normal load.
10 Modified direct shear apparatus (Roscoe, 1953) (conceptual system)	Shear strength		6 E	U	300 (E)	U	2	3	1	1	3	This conceptual system offers advantage over conventional direct shear test w/ respect to pattern of shear plane distribution within soil sample.
11 Squeeze test (Jurgenson, 1934)	Shear strength	Compression of plastic materials between rigid plates	U	U	U	U	2	2	1	1	3	Unique test based on principles of rheology for determination of shearing resistance in plastic materials. No apparent application to lunar soils.
12 Volumeasure Soiltest, Inc.	In-place density	Employs water-filled balloon and graduated cylinder to measure hole volume	20 (E)	0	1000 (E)	1	2	1	1	1	2	Use of fluid apparently renders apparatus unsuitable for lunar use. Requires preparation of hole and measurement of sample weight therefrom.

SHEET 1 OF 1

INSTRUMENT EVALUATION SHEET

STUDY GROUP Soil Mechanics

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Sand density cone CN-989 Soiltest, Inc.	Volume		20 (E)	0	1400 (E)	1	2	1	1	1	2	Use of sand cone apparatus in lunar environment may be impeded by clogging due to adherence of sand particles.
2 Consolidometer apparatus Soiltest, Inc.	Load settlement	0 - 20 Kg/cm^2 pressure applied by weights and 20 to 1 lever system	100 (E)	0	2500 (E)	1	variable	4	1	1	2	Terrestrial use requires approx 24 hr. Lunar tests could be applied very rapidly in absence of hydrodynamic forces.
3 Harvard miniature compaction apparatus CN-435 Soiltest, Inc.	Density-compactive effort relationship	Spring loaded compaction tampers 20lb and 40 lb	15 (E)	0	1000 (E)	U	3	1	1	1	2	Density-compactive effort relationship would require only compaction mold, mold holder, and compaction tamper in addition to spring balance. Proposed use is not conventional compaction test
4 Miniature CBR set CN-465 Soiltest, Inc.	Modulus of penetration resistance	0 - 500 lb compression range. Hand cranked through gear train. Sensitivity 0.1 lb	40 (E)	0	2000 (E)	1	4	2	1	1	2	Miniaturized laboratory CBR test. May be useful for determination of parameters and design information for lunar basing.
5 Tethered sphere (conceptual device for rapid evaluation of pedestrian support)	Bearing capacity	Design criterion is that bearing capacity to support tossed sphere is adequate for man.	2 (E)	0	200 (E)	U	1	1	1	1	3	Anticipated use of this device will enable testing of ground several feet ahead of an astronaut, beyond the reach of a staff.
6 Soil truss, Mark II (Harroun, 1953)	Shear strength	Useful terrestrial range is soils w/ ultimate bearing capacity 400 lb/ft^2 to 1200 lb/ft^2	10 (E)	0	700 (E)	1	2	1	1	1	2	Cohesive strength measured with this instrument varies greatly as a function of loading rate. Properly used, instrument produces rational values of shear strength parameters for general use.
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INSTRUMENT EVALUATION SHEET

SHEET 1 OF 3

STUDY GROUP Surveying, Mapping, Photography

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Pilotage & Dead Reckoning with LEM Navigation Equipment (Sears, 1964)	Lunar position	U	on LEM	on LEM	on LEM	2	on LEM	on LEM	1	1	1	Used on board LEM during lunar descent and landing.
2 Lunar Maps	"	1/25,000 scale (± 23 ft resolution)	1 with case	0	18	2	1	1	1	1	1	Maps will be prepared from orbiter photography.
3 Scales Dividers Protracter	"	± 5-25 ft. ± 0.25°	0.25	0	13	1	1	1	1	1	2	Accuracy will depend upon map scale. Used for measuring, plotting distances and bearings.
4 Theodolite w/tripod Wild T-12 Brochure	Bearings, Vertical angle, Distance	Angles: ± 1' hor., ± 2' vert. Stadia distances	6.6	0	Theod. 50 Tripod 740 E	1	1	1	1	1-2	2	Level bubble would require heating. Dials need illumination at night.
5 10 Second Theodolite Kern DKM-1 Brochure	"	Angles: ± 10"	18	0	Theod. 150 Tripod 740 E	1	1	1	1	1-2	2	See Line 4. Weight could be less with aluminum tripods.
6 1 Second Theodolite Wild T-2 Kern DKM-2	"	Angles to 1"	26	0	Theod. 324 Tripod 740 E	1	1	1	1	1-2	2	"
7 Camera Transit (Bazhaw, 1964)	Bearings, Elev.diff. Distance	Angular accuracy: ~6". Magnetic bearings 1/4°. Distance to 1/500	15	Few watts for camera drive	2600	2	1	1	1	1-2	2	See Line 4. Will be used with Hand Camera, line 7. Weight & Vol. of Camera included.
8 Hand Camera Graflex Lunar Camera	Distance Elev.diff. Photo background	Stereo or non-stereo. Two film rolls. Level bubbles, mil scale.	4.5	Few watts for camera drive	70	2	1	1	1	1	3	See Line 4.
9 Steel Tape Lufkin No. 4100	Distance	0.1 ft over 200 ft	5	None	9	1	1	1	1	1	2	
10 Surveyors Arrows K&E Steel Arrows No. 830212	Survey accessory, Photo reference markers	NA	1	None	14	1	1	1	1	1	2	
11 LEM TV	Tracking for bearings & distance	LEM equipment	LEM equipment	LEM	LEM	2	1	2	1	1	1	
12 LEM TV Tracker (Angle Encoder, Ranging Instrument TI-Apparatus	Distance Azimuth	Distance by Phase Comparison to one foot resolution Azimuth to ± 1/4°	4.5	10 watts	150	2	1	2	1	1	4	Proposed development. Uses small transmitter carried by astronaut.

SHEET 2 OF 3

INSTRUMENT EVALUATION SHEET

STUDY GROUP Surveying, Mapping, Photography

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.³	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Astrolabe (with level) Zeiss NI-2	Astro-nomic position	± 1" mean square error	20	3 "D" Cells	500 E	2	4-5	1-2	1	1	2	
2 Astrolabe (as accessory to Wild Theodolite	"	Accuracy ~1"	2	3 "D" Cells	10-20	2	4-5	1-2	1	1	2	Weight & Volume in addition to 1" theodolite.
3 Zenith Camera Lab Geodetics Corp Model 20	"	"	40-60 E	12 rolls DC auto battery	25,000 E	2	3	1	1	1	2	
4 Theodolite T-3 Chronograph Radio Receiver Wild Brochure	"	Accuracy: ~ 0.2 ' on circles	100 lb. E	Few watts	2500-3000	2	5	2-3	1	2	2	This constitutes survey set for astronomic observations of azimuth and geographic position.
5 Strike Camera J. Maurer 220G	LEM position (Descent photo)	2-1/4 x 2-1/4" format, focal plane shutter: 1/500, 1/1000, 1/2000 sec. 6 frames/sec.	12 lbs 2/125' film	9.2 amps 24-29 v. DC	480	1	1	1	1	1	2	No image motion control. Would require fast film.
6 Strike Camera Itek Day/Night Camera	"	2-1/4 x 2-1/4" format. IMC -0 to 3 in/sec. Graflex shutter. 1/60, 1/125, 1/250, 1/500	6 lbs. w/50' film	28 v. DC 75 watts	217	1	1	1	1	1	2	Has image motion control, needed so relatively slow, more radiation resistant film can be used. View angle 58.6°.
7 Reconnaissance Camera K-50A Chicago Aerial Ind.	"	4-1/2 x 4-1/2" format. 1-3/4" lens 104°48' view angle. IMC 0.15 to 10.8 in/sec. 3 exp/sec.	40.2 w/100'film	10.0 amps (avg) 28 v. DC	2400	1	1	1	1	1	2	Good lens coverage for picture of landing area at 1000'. IMC for slow film. Good format size. Film capacity adequate.
8 Reconnaissance Camera HR-320 Hycon Mfg. Co.	LEM position from orbit	40" lens focal length, 9x9" format View angle 13°. Focal plane	135 w/390'film	150 watts 28 v. DC	U	1	1	1	1	1	2	Field of view small for photos from orbit. Heavy.
9 High Acuity Camera LG-77A Hycon Mfg. Co.	"	48" lens focal length, 4.5x4.5" format. View angle 5.2° IMC	276 w/250'film	200 watts 28 v. DC	U	1	1	1	1	1	2	"
10 Sun Gun Sylvania	Illumin-ation for photo-graphy	20,000 center beam candle power 3400°K color temp. 30 minutes life	17-1/2 w/battery	250 watts at 30 volts	250	2	1	1	1	1	2	Too heavy for 30 minute use.
11 Braun F-25 Electronic Flash	"	Guide No. 40 for ASA 25 60 flashes 8 seconds cycle	0.8 w/battery	U	19	1	1	1	1	1	2	Should have more capacity, higher guide number.
12 Johnson Elev Meter (Speert, 1962)	Position, Elevation	Accuracy: ~1' elev ~ 1/2000 distance	1000-2000	U	U	3	1	3	2	1	2	Designed for vehicle mounting. Uses distance wheel and integration of pendulum inclinometer output.

INSTRUMENT EVALUATION SHEET

STUDY GROUP Surveying, Mapping Photography

INSTRUMENT AND DATA SOURCE	MEAS-URAND	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Stadia Tapes for LEM K&E.E Pattern	Distance	Patterned target for measurement of intercept interval w/theodolite	1	50 w(night) 0 (day)	20	1	1	1	1	1	2	
2 Stadia Targets for Camera (Bazhaw, 1964)	"	Patterned target for measurement of intercept interval on mil scale	0.25	E	20	1	1	1	1	1	3	
3 Subtense Bar Wild	"	Intercept target for theodolite; accuracy function of theod.	15	0	320	1	1	1	1	1	2	
4 Hand Level K & E	Elevation	Sight elevation changes on studia rod, accuracy: 5'/1000' (1/4°)	1	0	6	1	1	1	1	1	2	
5 Range finder Wild Hunters Type	Distance	Optical range finder accuracy: 76'/1000'	1.5	0	27	1	1	1	1	1	2	
6 Geodimeter Model 4 D AGA Corp.	"	Accuracy: 0.04 ft. in 3-20 miles, $\pm$ ($5\times10^{-7}\times D$)	121 w/power supply	300-400 watts	5660	2	2	2	1	1	2	Pulsed optical ranging on passive reflector.
7 Micro-Distancer Model MRA3 Tellurometer, Inc.	"	Accuracy: $\pm$ 1 cm $\pm$ 1/10^6	98 (w/power supply)	12 v DC	5160	2	2	2	1	2	2	Phase comparison of microwave signal. Requires transmitter and receiver units.
8 Electrotape Model DM-20 Cubic Corp.	Distance	Accuracy: $\pm$ 1 cm $\pm$ 1/3×10^5	90 (w/power supply)	4A 12 v DC	8480	2	2	2	1	2	2	"
9 Earth Compass-Inclinometer	Azimuth, Dip	Gunsight transit using earth as reference Accuracy: $\pm$ 25° C	1	None	18	1	1	1	1	1	5	Conceptual instrument.
10 Photo printer	LEM position	Enlarges descent camera negative to 10" x 10" print	2.5	Few watts	310 E	1	1	1	1	1	5	Conceptual accessory.
11 Sun Compass	Camera, photo orient, color, gray scale, sun altitude	Shadow pin on leveled compass rose. Standard grey and color scales	0.3	0	3	1	1	1	1	1	5	Used to orient photographic features relative to sun. Requires a bullseye level, and pin mounted vertically on compass rose.
12 Transponder	Distance to landing site	Transmits coded signal upon interrogation	2 E	1 w oper 0.1 w standby	35 E	1	1	1	1	1	3	For post-Apollo missions to navigate relative to original LEM landing site. At least 1 year life desired.

SHEET 1 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	[illegible]	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Hand-Operated Core Drill Model DR-790 Soiltest, Inc.	Undis-turbed	Rotary Boring 7/8 in. core to depth of 50 ft.	36	5.5 hp	1000 E	2	Function of material	2	1-2	1	2	Gas powered but could be modified to battery power.
2 Core Drill U. S. Dept. of Interior Bartlesville, Okla.	"	Rotary boring 7/8 in. core - 12in. length	7	12 v Nicad	U	2	"	2	1-2	1	2	Will drill five 12-in. sandstone cores with one battery. Normally cooled by water. <u>Oil & Gas Journal</u>, "Techniques of Outcrop Rock Sampling," Sept. 23, 1963.
3 Junior Core Drill Model DR-1312 Soiltest, Inc.	"	Rotary-Boring	40	110 v-ac	U	2	"	2	1-2	1	2	Weight includes transformer for 110-v but not power source.
4 SKIL Roto-Hammer Model #726 SKIL Corp.	"	Three-way action 1. Rotary 2. Impact 3. Rotary-Impact	13.7	5.5 amps 115 v-ac	300 E	2	"	2	1-2	1	2	1-1/4 in - 1-1/2 in core bits - 2400 blows per minute - 520 rpm. May be unduly complex for lunar environment.
5 SKIL Battery Drill Model #203 SKIL Corp.	"	Rotary boring 550 rpm - no load	7.6	12-v NiCd battery	180 E	2	"	2	1-2	1	2	Too small for coring samples. Battery pack idea useful. Can make 100 - 1/4 in. holes in 16 gauge steel on one battery.
6 Geologists Hammer	Non-representative to Un-disturbed	Breaking, chipping - and chiseling	1.5	None	20	1	"	1	1-2	1	2	Slight modifications may be in order for lunar use. Use nonmagnetic metal or heavy plate for hammer head.
7 Hand Saw	Un-disturbed	Sawing medium hard rock	1 E	None	10 E	1	"	1	1-2	1	3	Modify or design small hand-saw with tungsten-carbide serrated cutting edge.
8 Knife (Bowie Type)	Representative to Undisturbed	Cutting, scraping soft or friable rock	0.5	None	4 E	1	"	1	1-2	1	2	Need hardened cutting edge. Possibly incorporate saw and knife into one tool--saw-knife.
9 Electro-Thermal Forcing General Electric Experimental	"	Breaking by use of high voltage	U Expected to be great	Large amount of power needed	U	U	U	U	U	U	3	Experiments with breaking rock using radio frequency electric power. <u>Mining Engineering</u>, Nov. 1961.
10 Sampling Spoon CN-995 Soiltest, Inc.	Non-representative to Representative	Scraping, digging unconsolidated material	0.5	None	6 E	1	1	1	1-1	1	2	Probably simplest method of retrieving small specimens and loose, unconsolidated material. No element of danger.
11 Sand Scoop CN-502 Soiltest, Inc.	"	Scrape, dig and shovel unconsolidated material	1 E	None	52	1	1	1	1-1	1	2	Scoop is cast from aluminum - will not contaminate magnetic properties of sample.
12 Post spade DR-27 Soiltest, Inc.	"	Dig unconsolidated to soft rock	5	None	100 E	1	1	1	1-1	1	2	Large samples - hole digging for subsurface samples.

SHEET 2 OF 8 INSTRUMENT EVALUATION SHEET STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Soil Conservation Bucket Auger DR-30 Soiltest, Inc.	Non-representative to Representative	Dig unconsolidated to soft rock	12	None	378 E	2	Function of Material	1	1-1	1	2	Acquires large sample. Has moving parts - steel bits and buckets.
2 Grain Sampler DR-45 Soiltest, Inc.	"	Rotary Action for loose soils only to 2 feet	25	None	150 E	1	"	1	1-1	1	2	Good for loose materials. Has moving parts.
3 Retractable Plug Sampler DR-49 Soiltest, Inc.	"	Rotary and Impact Action for loose and soft soils to 50 feet	300	U	U	1	"	2	1-1	1	2	Obtains sample at desired depth. Has moving parts.
4 Spiral Slot Sampler DR-51 Soiltest, Inc.	Non-representative	Rotary Action in loose and hard soils to 2 feet	10	U	72 E	1	"	1	1-1	1	2	Has steel nose, cutting edges.
5 Sand Pump Sampler DR-60 Soiltest, Inc.	"	Pump, Piston, Plunger 5-ft depth	40	U	630 E	2	"	2	1-1	1	2	No moving parts - operation depends on suction methods for retrieving sample. Questionable whether feasible on lunar surface.
6 Closed Spiral Auger DR-197 Soiltest, Inc.	"	Rotary Action 8 - 16 in. E.	6	None	700 E	2	"	1	1-1	1	2	No moving parts. Weight does not include handle.
7 Ship Auger DR-200 Soiltest, Inc.	"	Rotary Action 8 - 16 in. E.	6	None	700 E	2	"	1	1-1	1	2	For sticky soils only. No moving parts. Weight does not include handle.
8 Jamaica Open Spiral Auger DR-203 Soiltest, Inc.	"	Rotary Action 8 - 16 in. E.	6	None	700 E	2	"	1	1-1	1	2	For loosely compacted soil deposits. No moving parts. Weight does not include handle.
9 Power Earth Auger DR-450 Soiltest, Inc.	"	Rotary Action to 30 ft.	79	9 hp gas engine	U	2	"	3	2-2	2	2	Gasoline-powered. Moving parts - require lubrication.
10 Hand-Operated Power Auger DR-462 Soiltest, Inc.	"	Rotary Action 5 ft. E.	29	2-1/2 hp air-cooled engine	U	2	"	3	2-2	1	2	Gasoline-powered. Moving parts - require lubrication. Modification simple to batteries and coring.
11 Laboratory Tongs G-120 Soiltest, Inc.	Representative to Undisturbed	Hinge & Spring Action	0.5	None	2 E	1	1	1	1-1	1	2	
12 Midget Impinger U.S. Bureau of Mines I.C. 7076, Schrenk & Feicht, 1939	Representative	Aspiration plus liquid entrapment	10 E	U	200 E	2	3	1	2-2	1	2	Results vary only 10% from large impinger. Requires creating vacuum for aspiration of airborne particles. Requires use of liquid.

SHEET 3 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	[illegible]	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 "Unimaster" Self-Contained Dust Collector "The Engineer" Mar. 18, 1960, p.480	Representative	Aspirator plus Mechanical Entrapment	U	U	U	1	5	2	1-1	1	2	Requires a blower for creating suction through a filter. Fan cap. 0.0 cfm @ 6.2 in. water gauge to 765 cfm @ 3.3 in. water gauge. Very bulky.
2 Grit & Dust Sampler "The Engineer" Jan. 15, 1960, p.108	"	Aspirator plus Mechanical Entrapment	U	U	U	1	3	3	1-2	1	2	Requires a blower for creating suction through a filter. 80 cfm for 30 min. Very bulky.
3 Battery Air Sampler B-13 Gelman Instr. Co. Chelsea, Mich.	"	Aspirator plus Mechanical Entrapment	24	NiCd Batteries	360 E	1	1	1	1-1	1	2	Requires use of vacuum pump to obtain sample. Can sample 13 liters/min. for 1-1/2 hours. Very compact.
4 Hurricane Air Sampler #16002 Gelman Instr. Co. Chelsea, Mich.	"	Aspirator plus Mechanical Entrapment	12	115 v. 3/4 h.p.	450	1	1	1	1-1	1	2	Requires use of vacuum pump to obtain sample; 150 cfm.
5 Shielded Syringe Model S-266 R.E.A.C. 665 Merrick Rd. Lynbrook, N.Y.	"	Aspirator	2 E	None	6 E	1	1	1	1-1	1	2	Beta shielded syringe. Syringe is interchangeable. See also "Air Particulate & Continuous Air Monitors" by "Victoreen", 5806 Hough Ave., Cleveland 3, Ohio.
6 Thermal Precipitator Many Models	"	Aspirator plus Thermal Precipitation	U	U	U	1	5	2	1-1	1	2	Particulate matter precipitated on two glass slides located on both sides of a heated wire. Does not shatter particles.
7 Dustfall Collectors Many Models	"	Passive operation Particle count vs. Time	U	None	U	2	5	1	1-1	1	2	Merely a wide mouth bucket. Simple modification (baffle & stand) would yield a crude instrument for erosion & deposition rates.
8 Freon-Powered Midget Impinger	"	Aspirator Liquid or Solid Entrapment	6 E	Freon Gas	110 E	2	5	2	1-2 P	1	2	Suction of air through nozzle at high velocity deposits dust in water after striking plate. Shatters some particles.
9 Hexhlet Sampler	"	Aspirator plus Mechanical Equipment	U	U	150 E	2	5	2	U	1	2	Sorts sizes and does not have problem of agglomerate formation as does the impinger filter.
10 Planchet Forceps S-322 R.E.A.C. Lynbrook, N.Y.	Representative to Undisturbed	Spring and Hinge action	0.3 E	None	2 E	1	1	1	1-1	1	2	3 finger (retractable) steel forceps for picking up small objects (1-1/4 in.)
11 Konimeter	Representative	Aspirator plus Mechanical Entrapment	U	U	50 E	2	U	U	1-1	1	2	Shatters particles - Inefficient with particles of less than one micron.
12 Leitz Tyndalloscope	"	Measures degree of light scattering through air sample	U	U	140 E	2	U	U	1-1	1	2	Needs more investigation. Measures degree of light scattering created when a beam of light is directed through an air sample.

SHEET 4 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Electrostatic Precipitator	Representative	Aspirator Corona Discharge	U	U	U	2	U	U	1-1	1	2	"The Collection of Silica Fume with an Electrostatic Precipitator," Air Pollution and Control Association Journal, Vol. 8, No. 1, 1958.
2 Aerosol Photometer Southern Research Institute Birmingham, Ala.	"	Aspirator Liquid Entrapment	10	Battery	320 E	2	U	1	1-1	1	2	Photo-electric particle sizer and counter--May have application.
3 Alnico Magnet Edmund Scientific	Representative to Undisturbed	Magnetic Attraction Est. 2 lb. Pull	0.3	None	0.5	1	1	1	1-1	1	2	
4 Model Air Sampler, MX 1191 TDQ1, Signal Corp Engr. Labs. Ft. Monmouth, N.J.	Representative	Aspirator Ionization	15	three 2 v. wet cells	650 E	2	3	1	1-1	1	2	Blower for collecting dust simulates breathing. Has ionization chamber for alpha and beta determinations.
5 Dart Valve Bailer DR-188 Soiltest, Inc.	"	Pressure Valve	72	None	600 E	1	1	1	1-1	1	2	Standard length is 10 feet. Could use same principle in miniature system.
6 Kemerrer Sampler DR-1002 Soiltest, Inc.	"	Open valve with release for closing	8	None	U	1	1	1	1-1	1	2	400 cc. capacity.
7 Bacon Sampler AP-256 Soiltest, Inc.	"	Pressure valve	6	None	40 E	1	1	1	1-1	1	2	16 oz. capacity.
8 Split tube Sampler with liner DR-144 Soiltest, Inc.	Representative to Undisturbed	Rotary and Rotary-Impact Action	20	None	80 E	2	Function of material	1	1-1	1	2	Sample retained in removable liner. Samples to 2 foot lengths.
9 Special Split Tube Sampler DR-130 Soiltest, Inc.	"	Rotary Action	18	None	180 E	2	"	1	1-1	1	2	Obtains relatively undisturbed sample to lengths of 2.5 feet.
10 Stationary Piston Sampler DR-1798 Soiltest, Inc.	"	Rotary and Impact Action	36	None	95 E	2	"	1	1-1	1	2	Operation depends on suction methods for retrieving samples. Samples up to 2 foot lengths.
11 Thin wall Sampler, Open-Type DR-164B Soiltest, Inc.	Representative	Rotary and Impact Action	24	None	300 E	2	"	1	1-1	1	2	Samples up to 3 foot lengths. Very simple to operate. Sample is retained in sampling tube and can be capped at both ends.
12 Mackintosh Boring and Prospecting Tool DR-461 Soiltest, Inc.	"	Rotary Action	12 E	None	270	2	"	1	1-1	1	2	Has sampling capacity to 50 foot depth.

SHEET 5 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Sleeve Auger Maclean-Rolfe Roads & Road Constr. Jan. 1945	Representative	Rotary Action	U	None	U	1	Function of material	1	1-1	1	2	Short Samples--Auger cuttings are forced up a tube for preserving.
2 Thinwall Split Barrel Sampler Cooling & Smith	Representative to Undisturbed	Rotary Action	U	None	U	1	"	U	U	U	2	
3 Surface Soil Sampler Corp of Engr. CN-1030 Soiltest, Inc.	"	Rotary and Impact Action	36	None	U	2	"	1	1-1	1	2	Sampler is 3 in. diam. and 2-13/16 in. long. Simple instrument--could be made lighter and more compact.
4 Little Beaver Power Soil Sampler Haynes Mfg. Co.	Representative	Rotary Action	48	2.5 hp Gasoline Engine	U	1	"	2	1-2	1	2	Gas powered--Could be converted to battery and made smaller. Auger.
5 Multiple Soil Sampler P. J. Parsons	"	Rotary Action	U	None	40 E	1	"	2	1-2	2	3	A unique sampler for acquiring samples at different depths in one operation. Jour. of Soil Mech. div. of A.S.C.E. Vol. 87, SM6, Dec. 1961.
6 Lunar Drill Model J.P.L. Report # 32-374 H. Carl Thorman	Non-Representative to Representative	Impact Action	30	600 w.	U	1 P	"	2	1-2	1	1	Produces a non-representative sample of chips. 3000 bpm, 1-1/4 in. hole with 50 lb. force. Can penetrate 24in. of Harris granite with 1000 w-hr.
7 Lunar Drill Model Armour Res. Found. Report # 8208-6	"	Impact Action	60.9	1000 w-hr.	U	1 P	"	2	1-2	1	1	Sample is chips only. Needs to be pressurized with a gas to operate impact device. 0.75hp-24v. with 50 lb force makes 1-5/8 in. hole 5 feet deep. Can penetrate 18" of gabbro with 1000w-hr.
8 Lunar Drill Model Texaco, Inc. J.P.L. Con. N-33552	"	Impact Action	35	375 w	U	1 P	"	2	1-2	1	1	Produces chips only. Penetrates Berea Sandstone at rate of 1/2 in. per minute with 1-1/4 in. hole.
9 Lunar Drill Model Hughes Tool Co. J.P.L. Con. N-33553	"	Impact Action	60	U	U	U	"	2	1-2	2 P	1	Produces chips only.
10 Syntron Electric Hammer Drill No. 26-RO	"	Rotary and Impact Action	28.7	1200 w. 15 amp.	450 B	1	"	1	1-1	1	2	Can be used as coring or impact device. 3600 bpm plus rotation.
11 Martin Minimum Reaction Space Tool Black & Decker	Representative to Undisturbed	Rotary Action	8	5.5v 15 amp.	430 B	1	"	1	1-1	1	1	Torque: Reactive 0.0116 ft-lb. Output 15-40 ft-lb.--Built as space tool but could be modified to sampler.
12 Swedish Increment Hammer Keuffel & Esser	"	Impact Action	3	None	14 E	1	"	1	1-1	1	2	Core 0.157 in. by 3/4 in. length. Built as sampler for forestry service.

SHEET 6 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Swedish Increment Borer Keuffel & Esser	Representative to Undisturbed	Impact Action	2 E	None	10 E	1	Function of material	1	1-1	1	2	Core 6 in. by 0.19 in. diam. Built as sampler for forestry service.
2 Denison Sampler DR-471 Soiltest, Inc.	Undisturbed	Combination Rotary and Impact Action	24	None	350 E	2	"	2	1-2	1	2	Primarily to be used with drill rig but can be used with hammer & pressure rotation.
3 Soil Sampling Tube A-2 Soiltest, Inc.	"	Combination Rotary and Impact Action	6	None	350 E	2	"	2	1-1	1	2	Good for soft, cohesive soils.
4 Shelby Tube Thinwall Sampler H.A. Mohr	"	Combination Rotary and Impact Action	U	None	U	2	"	1	1-1	1	2	Sample is preserved in sample tube.
5 Auger Core Barrel, Single Tube, Slater-Byers: Bul. 231, Dept. of Agric., 1931	"	Rotary Action	U	None	U	2	"	1	1-1	1	2	Core must be removed and placed in container.
6 Auger Core Barrel, Double Tube, V.R.Smith, Report, Cal. Research Corp., 1944	"	Rotary Action	U	None	U	2	"	1	1-1	1	2	Core retained and preserved in inner tube. Possible to modify to battery power and diamond cutting edges.
7 Battery Power Pack Rockwell Mfg.Co. Porter-Cable Div.	Accessory item	N.A.	3.8	10 v. 40-45W-hr	36 E	1	3	1	1-1P	1	2	
8 Masonry Drills Relton Corp. Pasadena, Calif.	"	Rotary or Impact	Function of size	U	Function of size	1	Function of material	1	1-1	1	2	Can be utilized in presently available power tools. Cuts cores.
9 Hole Saw Carbide-tipped Relton Corp.	"	Rotary	"	U	"	1	"	1	1-1	1	2	For obtaining larger cores than masonry drills.
10 Magnetic Couplings for totally sealed systems	"	Rotary or Impact Action	U	U	U	U	Function of type tool and material	1	1-1	1	2	Apply principle to hermetically sealed systems.
11 Thor High Freq. Electric Tools Thor Mfg. Co.	Non-Representative to Undisturbed	Rotary or Impact Action	U	U	U	U	Function of material	1	1-1	1	2	This type tool may be applicable to sampling if weight can be lowered.
12 Baker Cable Tool Core Barrel No. 520 Baker Oil Tools Inc.	Undisturbed	Rotary Action	U	U	U	1	"	U	1-1	2	2	Dependable tool--Standard type core barrel for undisturbed sampling.

SHEET 7 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME IN.^{3}	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Double Tube Core Barrel DR-373AX Soiltest, Inc.	Undisturbed	Rotary Action	12	U	U	2	Function of material	U	1-2	U	2	Inner tube is used for sample storage.
2 Reaction Container CT-388 Soiltest, Inc.	Sample Container	Clamp cover	4	None	7 E	1	1	1	1-1	1	2	May be suitable for ultravacuum tight containers if modified. 75 ml. capacity.
3 Tin Sample Boxes LT-80 Soiltest, Inc.	"	Outside fitting cover	0.1	None	12 E	1	1	1	1-1	1	2	Simple can with tightly fitting cover. May be suitable for samples that do not require an ultravacuum tight seal. 8 oz. cap.
4 Sample Jars LT-25 Soiltest, Inc.	"	Screw cover	0.4	None	15 E	1	1	1	1-1	1	2	8 oz. cap.
5 Welded Bellows Borg-Warner	"	Modify for flush cover	0.3 E	None	10E	1	1	1	1-1	1	3	Item warrants study for modifying to container use. Would have volume flexibility.
6 Filter Funnels Gelman Instrument	"	Modify for screw or clamp cover	U	None	U	U	1	1	1-1	1	3	Item warrants study for modifying to container use.
7 Metal Box Rectangular Z48-80 Zero Mfg. Co.	"	Inside or outside fitting cover	U	None	45	1	1	1	1-1	1	2	Has outside fitting cover which can be used with gasket.
8 Metal Container Cylindrical ZR 74 Zero Mfg. Co.	"	Inside or outside fitting cover	U	None	40 E	1	1	1	1-1	1	2	Cylindrical shape for large core samples.
9 Metal Container Core Size HU-694 Hudson Tool & Die	"	Inside or outside fitting cover	U	None	12 E	1	1	1	1-1	1	2	Obtainable in stainless steel. Good size for core samples.
10 Star Drill Syntron	Accessory	Reciprocating Action	0.5	U	3 E	1	Function of material	1	1-2	1	2	
11 Sabre Saw Syntron	"	Impact Action	0.5 E	U	3 E	1	"	1	1-2	1	2	
12 Core-Style Hammer Drill Relton Corp.	"	Impact Action	1.5 E	U	15 E	1	"	1	1-2	1	2	

SHEET 8 OF 8

INSTRUMENT EVALUATION SHEET

STUDY GROUP Sampling

INSTRUMENT AND DATA SOURCE	TYPE SAMPLES	OPERATING CHARACTERISTICS & DYNAMIC RANGE	WEIGHT LB	POWER	VOLUME $IN.^3$	RELIAB. RATING	OPERATE TIME RATING	SETUP TIME RATING	HAZARD RATING	NUMBER OF PEOPLE	STATE OF DEVELOP.	REMARKS AND ADDITIONAL ENGINEERING DATA
1 Stone Point Syntron	Accessory	Impact Action	0.5 E	U	3 E	1	Function of material	1	1-2	1	2	
2 Digging Chisel (clay digger) Thor Power Tool	"	Impact Action	2.0 E	U	50 E	1	"	1	1-2	1	2	
3 Soil Sampling Tube	Representative to Undisturbed	Impact and Pressure	0.5 E	None	15	1	"	1	1-1	1	3	Include as sample container (ultra-vacuum tight). This tube will be open at both ends and must be sealed on both ends.
4												
5												
6												
7												
8												
9												
10												
11												
12												

APPENDIX D

CITED REFERENCES AND BIBLIOGRAPHIES

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APPENDIX E

SELECTED MEASUREMENTS AND EXPERIMENTS (BY DISCIPLINE)

APPENDIX E

SELECTED MEASUREMENTS AND EXPERIMENTS (BY DISCIPLINE)

A. FIELD GEOLOGY AND MINERAL EXPLORATION

1. Mineral Identification
   a) visual observation (magnet, sampling package)

2. Rock composition (petrography)
   a) visual observation, hand lens (sampling package)

3. Abrasive hardness
   a) visual observation (knife point, sampling package)

4. Rock texture: grain size, grain shape, proportion glass to crystal
   a) hand lens

5. Rock fabric: grain arrangement, grain distribution
   a) hand lens

6. Rock color
   a) visual observation

7. Dust boundaries, horizontal and vertical
   a) visual observation, staff, descent camera

8. Dust texture, consistency and composition
   a) visual observation, hand lens, staff (sampling package)

9. Geologic age and stratigraphic position
   a) visual observation, maps, staff, gyrocompass w/inclinometer, hand camera

10. Stratigraphic sequence
    a) visual observation, maps, staff, gyrocompass w/inclinometer, hand camera

11. Structures: kind, attitudes, and trends
    a) visual observation, maps, staff, gyrocompass w/inclinometer, hand camera

12. Areal gradations
    a) visual observation, descent camera, hand camera, maps (sampling package)

A. FIELD GEOLOGY (Cont'd)

13. Formation contacts
    a) visual observation, maps, staff, gyrocompass, hand camera

14. Bedrock exposures: altitude, extent, composition
    a) visual observation, maps, staff, gyrocompass, hand camera

15. Kind and amount of ore minerals
    a) visual observation, hand lens (sampling package)

16. Attitude and extent of mineral deposit
    a) visual observation, maps, staff, gyrocompass, hand camera

17. Localization of ore and its genesis
    a) visual observation (interpretation)

18. Surface reflectance (UV)
    a) reflectance radiometer

19. Surface reflectance (visible)
    a) reflectance radiometer

B. GEOMORPHOLOGY

20. Topographic mapping
    a) descent camera

21. Slope
    a) visual observation, maps, inclinometer

22. Occurrence of steep slopes
    a) visual observation, maps, hand camera

23. Determination of relief
    a) visual observation, hand camera, descent camera, staff, inclinometer, maps

24. Orientation of topographic highs and lows
    a) descent camera

25. Areal occupancy of topographic highs and lows
    a) descent camera

26. Planar shape of topographic highs and lows
    a) descent camera

B. GEOMORPHOLOGY (Cont'd)

27. Cross-sectional shape of topographic highs and lows
    a) visual observation, maps

28. Angle of repose
    a) inclinometer
    b) visual observation

29. Sorting or grading
    a) hand lens

30. Erosion
    a) visual observation

31. Transportation
    a) erosion particle movement sampler
    b) visual observation

32. Deposition
    a) visual observation, maps

33. Radiation damage (discoloration)
    a) visual observation

34. Micrometeorite accretion
    a) visual observation

35. Effects of thermal cycling
    a) visual observation

36. Sintering (Particulate radiation effects)
    a) visual observation

37. Vacuum outgassing
    a) visual observation
    b) line source pressure gage

C. COMPOSITIONAL DETERMINATIONS

38. Mineral composition (solid)

    a) X-ray diffractometer
    b) infrared spectrometer
    c) differential thermal analysis

C. COMPOSITIONAL DETERMINATIONS (Cont'd)

39. Chemical composition (solid)
    a) X-ray spectrometer
    b) UV-visible spectrometer
    c) neutron activation analyzer
    d) alpha scattering spectrometer
    e) neutron scattering
    f) gas chromatograph
    g) mass spectrometer
    h) gamma ray spectrometer
    i) alpha ray spectrometer

40. Chemical composition (gas)
    a) gas chromatograph
    b) mass spectrometer
    c) infrared spectrometer

41. Radioisotope composition
    a) gamma ray spectrometer
    b) alpha ray spectrometer

42. Stable isotope composition
    a) mass spectrometer
    b) neutron activation analyzer

43. Rock density
    a) gamma ray backscattering

44. Lunar atmospheric pressure
    a) Kreisman gage

45. Detection of life forms
    a) sample culture with pH readout
    b) sample culture with radioisotope readout
    c) gas chromatrograph
    d) mass spectrometer
    e) UV-visible spectrometer

D. RADIOLOGICAL MEASUREMENTS

46. Solar wind
    a) solar plasma spectrometer
    b) survey rate meter

D. RADIOLOGICAL MEASUREMENTS (Cont'd)

47. Solar flares
    a) particle spectrometer (scintillators w/photomultiplier tubes)
    b) survey rate meter

48. Magnetically trapped radiation
    a) survey rate meter

49. Lunar radioactivity
    a) gamma ray spectrometer
    b) portable survey rate meter with directional capability

50. Secondary radiation
    a) portable survey rate meter with directional capability
    b) gamma ray spectrometer

51. Chemical reactivity
    a) chemical reactivity detector

52. Cumulative radiative dose
    a) personal integrating dosimeter

53. Total ionizing dose rate
    a) survey rate meter

54. Particulate radiation flux
    a) solar plasma spectrometer
    b) particle spectrometer

55. Cosmic rays with magnetometer
    a) particle spectrometer, TI low-field helium magnetometer
    b) survey rate meter, TI low-field helium magnetometer

E. MICROMETEOROID MEASUREMENTS

56. Micrometeroid flux
    a) micrometeroid and ejecta detector

57. Trajectories, velocities and momenta of lunar ejecta
    a) micrometeoroid and ejecta detector

F. MAGNETICS

58. Susceptibility in situ
    a) Susceptibility bridge (JPL-Bollin modified Mooney type)

F. MAGNETICS (Cont'd)

59. Magnetic field: vertical and horizontal components, vector sum and direction
    a) TI low-field helium magnetometer

60. Magnetic field gradient: vertical and horizontal components
    a) TI low-field helium magnetometer

61. Anisotropy in susceptibility
    a) Susceptibility bridge (JPL-Bollin modified Mooney type)

62. Magnetic field: diurnal and secular variations of vertical and horizontal components, vector sum and direction at 1 point, MHD waves
    a) TI low-field helium magnetometer

G. ELECTRICAL

63. Resistivity in situ (passive)
    a) 4 electrodes, voltmeter cables

64. Spontaneous polarization in situ
    a) 2 electrodes, voltmeter, cables

65. Dielectric constant in situ
    a) probe dielectrometer

66. Resistivity in situ (active)
    a) ac/dc, pulse current source, 4 electrodes, voltmeter, cables

67. Electrical transients in situ
    a) ac/dc, pulse current source, 4 electrodes, voltmeter, cables

68. Anisotropy in resistivity
    a) ac/dc, pulse current source, 4 electrodes, voltmeter, cables

69. Seismic-electrics
    a) Cal Tech portable refraction seismic system with energy source, 2 electrodes, voltmeter, cables

70. Correlation of E and H currents: short term, 1 point
    a) TI low-field helium magnetometer, 4 electrodes, voltmeter, cables

G. ELECTRICAL (Cont'd)

71. Correlation of E and H currents: long term 1 point
    a) TI low-field helium magnetometer, 4 electrodes, voltmeter, cables

72. Electrostatics
    a) charged dust detector
    b) visual observation

73. Deleted

H. GRAVITY

74. Tidal gravity
    a) tidal gravity meter
    b) ITT-Lamont seismometer

75. Gravity
    a) quartz gravity meter

76. Gravity gradient
    a) gradiometer

I. SEISMIC

77. Short-period noise
    a) Cal Tech short-period seismometer
    b) ITT-Lamont seismometer

78. Seismicity and long-period noise
    a) Cal Tech long-period seismometer
    b) ITT-Lamont seismometer

79. Active seismic: very short range
    a) Cal Tech portable refraction seismic system, mechanical source

80. Active seismic: long range
    a) Cal Tech portable refraction seismic system, chemical source

J. THERMAL

81. Landing gear temperature
    a) platinum resistance element, resistance bridge

J. THERMAL (Cont'd)

82. Boot temperature
    a) copper-constantan thermocouple, sensor and reference units, millivoltmeter series circuit

83. Surface temperature
    a) platinum resistance loop

84. Subsurface temperature
    a) thermal conductivity probe (copper-constantan thermocouple)

85. Landing gear thermal conductivity
    a) thermal conductivity probe (thermocouple sensor)

86. Subsurface thermal conductivity
    a) thermal conductivity probe (thermocouple sensor)

87. Surface thermal diffusivity
    a) modified flash radiometer

88. Subsurface thermal diffusivity
    a) thermal conductivity probe (thermocouple sensor)

89. Surface heat flow
    a) Radiometric heat flow meter

90. Subsurface heat flow
    a) thermal conductivity probe, string of 6 platinum resistance thermometers, flexible tool w/impact-rotary impact components

91. Surface interstitial gas pressure
    a) line source pressure gage (3 sensors to cover span)

92. Subsurface interstitial gas pressure
    a) line source pressure gage, flexible tool w/impact-rotary impact components

93. Surface emittance and reflectance (IR)
    a) reflectance radiometer

K. SURVEYING, PHOTOGRAPHY AND MAPPING

94. Position of LEM by resection
    a) maps, theodolite w/tripod

K. SURVEYING, PHOTOGRAPHY AND MAPPING (Cont'd)

95. Distance from LEM of sample sites and SIP
    a) hand camera with mil scale, film, level indicator, night stadia target on LEM
    b) tracking transducer on LEM TV camera

96. Azimuth at LEM of sampling sites and SIP
    a) tracking transducer on LEM TV camera
    b) gyrocompass w/inclinometer

97. Elevation relative to LEM of sampling sites and SIP
    a) tracking transducer on LEM TV camera
    b) hand camera film, level indicator, night stadia target on LEM
    c) photo transit w/tripod

98. Orientation of rock samples
    a) gyrocompass w/inclinometer

L. SOIL MECHANICS

99. Bulk density of soil or dust
    a) gamma ray backscattering
    b) calipers, ruler, spring scale, flexible tool w/impact-rotary impact components
    c) soil sampling tube (sampling package)

100. Soil or dust color and variations
    a) visual observation

101. Soil depth or dust thickness
    a) staff
    b) Cal Tech portable refraction seismic system, mechanical energy source
    c) flexible tool w/impact-rotary impact components

102. Penetration resistance
    a) penetrometer on staff
    b) staff
    c) tethered sphere

103. Shear strength
    a) vane shear tester
    b) direct shear tester, flexible tool w/all components
    c) Surveyor soil mechanics device (modified w/frame, anchors)

L. SOIL MECHANICS (Cont'd)

104. Compaction
   a) Harvard miniature compaction apparatus (hammer, cylinder)

105. Bearing strength
   a) Surveyor soil mechanics device (modified w/frame, anchors)
   b) hand camera (special lens)

106. Microstructures of soil or dust
   a) hand lens, visual observation, hand camera (w/special lens)
   b) hand camera (w/special lens), flexible tool w/ all components, hand lens

107. Stratigraphic elements of soil
   a) hand camera (w/special lens), flexible tool w/ all components, hand lens
   b) hand camera (w/ special lens), (scoop, sampling package), visual observation

APPENDIX F

COMPUTER ANALYSIS INPUT DATA

APPENDIX F

COMPUTER ANALYSIS INPUT DATA

Contained in this appendix are the input data to the first computer program. The list of instruments or equipment item(s) is an inversion of the list of measurements which appears in Appendix E, and the column headed Measurement No. is a cross-reference to that appendix.

The instrument numbers assigned to individual items or assemblages of items do not run consecutively; omitted numbers are due to elimination of duplications and corrections to program. Renumbering to obtain a complete, consecutive set would have necessitated repunching of all computer data cards and was not considered warranted. Instrument numbers in this appendix are the index numbers which appear in the input data to the second computer program. The first and second computer programs are described in detail in Appendix G, where a sample computer run is also given.

The column headings, Number of Measurements (IGR) and Group Size (IGS) are defined in detail in Appendix G, also. Essentially, they are instructional input values required by the computer program for special handling of instrument-measurement combinations.

The classification group numbers assigned to each measurement under the fundamental lunar problem area headings are defined as follows:

I. It is irrelevant to this problem area.

II. It possibly contributes to this problem area, but not in a known, direct manner.

III. It contributes directly to this problem area, but is not considered important.

IV. It contributes directly to this problem area and is considered important but is not an essential measurement.

V. The measurement is considered important to this problem area and is classified essential.

The last four columns contain the estimated payload cost of performing the listed measurement with the indicated instrument(s) or equipment item(s). A value for power appears only if projected use of the instrument requires power from the primary power supply on board the LEM.

If the instrument or equipment is to be portable for use by the astronaut during his traverses or to be left for remote operation in a geophysical observatory, power (or rather energy) requirements are converted into equivalent weight and volume and added to the estimated weight and volume, respectively, of the instrument itself. Values entered in the time column are estimated operating and setup times required of the astronaut in order to perform the measurement. The actual measurement time could be considerably longer if the instrument is capable of unattended operation after activation.

INSTRUMENT NO.*	INSTRUMENT(S) OR ECUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF: LUNAR SURFACE	ORIGIN, HISTORY, AGE OF: EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN.³)	POWER (WATTS)	TIME (MINUTES)	
1.	Visual observation, hand lens, staff (sampling package)													
	a) dust texture, consistency and composition	8		1	III	IV	IV	IV	III	2.6	11	0	8	
2.	Probe dielectrometer													
	a) dielectric constant in situ	63		1	II	II	I	IV	I	2	40	0	10	
3.	Visual observation, maps													
	a) cross-sectional shape of topographic highs & lows	25		2	III	IV	IV	IV	II	0.5	10	0	4	
	b) deposition	30			IV	IV	III	V	II	0.5	10	0	5	
4.	Visual observation, staff, descent camera													
	a) dust boundaries, horizontal and vertical	7		1	V	V	IV	IV	III	11	560	75	10	
6.	Visual observation, maps, staff, gyrocompass, hand camera													
	a) geologic age and stratigraphic position	9		6	II	II	III	V	IV	10.3	120	0	30	
	b) stratigraphic longitudinal cross-sections	10			II	II	III	V	IV	10.3	120	0	30	
	c) structures: kind, attitude, and trends	11			III	IV	IV	V	IV	10.3	120	0	25	
	d) formation contacts	13			II	II	II	V	IV	10.3	120	0	10	
	e) bedrock exposures; attitude, extent, composition	14			II	IV	IV	V	III	10.3	120	0	15	
	f) attitude and extent of mineral deposit	16			I	I	IV	IV	IV	10.3	120	0	10	
7.	Visual observation, hand lens (sampling package)													
	a) rock composition petrography	2		2	I	III	IV	V	IV	0.6	2	0	8	
	b) kind and amount of ore minerals	15			I	I	IV	V	IV	0.6	2	0	6	
8.	Hand lens													
	a) rock texture: grain size, grain shape, proportion glass to crystal	4		3	III	III	III	IV	IV	0.6	2	0	8	
	b) rock fabric: grain arrangement, grain distribution	5			II	III	III	IV	IV	0.6	2	0	8	
	c) sorting or grading	29			I	III	III	IV	II	0.6	2	0	10	
9.	Visual observation (knife point, sampling package)													
	a) abrasive hardness	3		1	III	IV	III	II	II	0	0	0	2	
10.	Cal Tech long-period seismometer													
	a) seismicity and long-period noise	78a		1	II	II	III	IV	V	17	720	0	12	
11.	Gyrocompass (w/inclinometer)													
	a) azimuth at LEM of sampling sites and SIP	96b		2	II	III	IV	IV	III	3	22	0	4	
	b) orientation of rock samples	98			I	I	II	IV	IV	3	22	0	8	
12.	Visual observation, descent camera, hand camera, maps, (sampling tools)													
	a) areal gradations	12		1	IV	IV	IV	IV	III	16.3	640	75	20	
13.	Visual observation, hand camera, descent camera, maps, staff, inclinometer													
	a) determination of relief	23		1	IV	V	IV	IV	II	17.3	660	75	10	
14.	Visual observation, maps, inclinometer													
	a) slope	21		1	IV	V	V	IV	II	1	20	0	10	

*Instrument numbers for computer analysis do not correspond with instrument numbers of Table V-1.

INSTRUMENT NO.	INSTRUMENT(S) OR EQUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF: LUNAR SURFACE	ORIGIN, HISTORY, AGE OF: EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN.³)	POWER (WATTS)	TIME (MINUTES)	
17.	Descent camera and printer													
	a) orientation of topographic highs & lows	24	4	1	II	IV	III	IV	II	9	550	75	0	
	b) areal occupancy of topographic highs & lows	25			II	III	IV	IV	II	9	550	75	0	
	c) planar shape of topographic highs & lows	26			II	III	II	IV	II	9	550	75	0	
	d) topographic mapping	20			V	V	V	V	IV	9	550	75	0	
18.	Visual observation, maps, hand camera													
	a) occurrence of steep slopes	22		1	V	V	V	IV	II	5.8	100	0	5	
19.	X-ray diffractometer													
	a) mineral composition (solid)	38a		1	I	III	IV	IV	IV	17.6	1200	60	15	
20.	Infrared spectrometer													
	a) mineral composition (solid)	38b		2	I	I	III	III	III	2	40	5	15	
	b) chemical composition (gas)	40c			III	II	II	III	II	2	40	5	15	
21.	Differential thermal analysis													
	a) mineral composition (solid)	38c		1	I	I	IV	II	II	10	860	200	10	
22.	X-ray spectrometer													
	a) chemical composition (solid)	39a		1	I	I	IV	IV	IV	33	360	25	15	
23.	UV-visible spectrometer													
	a) chemical composition (solid)	39b		2	I	I	III	III	III	12	1700	4	15	
	b) detection of life forms	45e			II	I	I	II	II	12	1700	4	15	
24.	Neutron activation analyzer													
	a) chemical composition (solid)	39c	2	1	I	I	III	III	IV	24	1740	0	15	
	b) stable isotope composition	42b			II	II	III	III	III	24	1740	0	15	
25.	Alpha scattering spectrometer													
	a) chemical composition (solid)	39d		1	I	I	III	III	III	5.2	560	0	15	
26.	Neutron scattering													
	a) chemical composition (solid)	39e		1	I	II	IV	II	II	30.3	870	0	20	
27.	Gas chromatograph													
	a) chemical composition (solid)	39f		3	I	I	II	II	II	13.2	690	15	15	
	b) chemical composition (gas)	40a			III	II	IV	IV	III	13.2	690	15	15	
	c) detection of life forms	45c			III	I	I	II	II	13.2	690	15	15	
28.	Mass spectrometer													
	a) chemical composition (solid)	39g	2	3	I	I	II	II	II	15	860	27	15	
	c) stable isotope composition	42a			II	II	III	IV	IV	15	860	27	15	
	b) chemical composition (gas)	40b			III	II	III	III	III	15	860	27	15	
	d) detection of life forms	45a			II	I	I	II	II	15	860	27	15	
29.	Gamma ray spectrometer													
	a) chemical composition (solid)	39h	4	1	I	I	II	II	II	12.1	860	0	15	
	b) radioisotope composition	41a			IV	II	IV	IV	IV	12.1	860	0	15	
	c) lunar radioactivity	49a			IV	I	III	IV	III	12.1	860	0	15	
	d) secondary radiation	50b			II	I	II	III	I	12.1	860	0	15	

INSTRUMENT NO.	INSTRUMENT(S) OR ECUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF LUNAR SURFACE	ORIGIN, HISTORY, AGE OF EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN.³)	POWER (WATTS)	TIME (MINUTES)
30.	Alpha ray spectrometer												
	a) chemical composition (solid)	39i		2	I	I	II	II	II	4.1	430	0	10
	b) radioisotope composition	41b			II	I	II	III	III	4.1	430	0	10
31.	Gamma ray backscattering												
	a) rock density	43		2	I	III	III	II	II	26.1	950	0	20
	b) bulk density of soil or dust	99a			II	II	III	IV	I	26.1	950	0	20
32.	Kreisman vacuum gage												
	a) lunar atmospheric pressure	44		1	II	II	IV	III	I	9	120	0	10
33.	Sample culture with pH readout												
	a) detection of life forms	45a		-2	V	I	I	III	II	1.2	28	1.3	5
34.	Sample culture with radioisotope readout												
	a) detection of life forms	45b			IV	I	I	III	II	1.5	1600	0	5
35.	Solar plasma spectrometer												
	a) solar wind	46a	2	1	I	I	II	III	III	15	410	0	5
	b) particulate radiation flux	54a			III	I	III	IV	III	15	410	0	5
36.	Survey rate meter												
	a) solar wind	46b	2	1	I	I	II	II	II	1.8	82	0	5
	b) solar flares	47b			IV	I	IV	II	II	1.8	82	0	5
	c) magnetically trapped radiation	48	2	1	III	I	II	II	IV	1	70	0.1	0*
	d) total ionizing dose rate	53			IV	I	IV	III	II	1	70	0.1	5
37.	Particle spectrometer (scintillaters w/photo multiplier tubes)												
	a) solar flares	47a	2	1	V	I	IV	III	II	31	325	0	5
	b) particulate radiation flux	54b			IV	I	IV	IV	III	31	325	0	5
38.	Portable survey rate meter with directional capability												
	a) lunar radioactivity	49b	2	1	IV	I	III	III	III	2	60	0	10
	b) secondary radiation	50a			II	I	II	II	I	2	60	0	10
39.	Chemical reactivity detector												
	a) chemical reactivity	51		1	V	IV	IV	III	III	0.5	17	0.02	10
40.	Personal integrating dosimeter												
	a) cumulative radiative dose	52		1	V	I	IV	I	I	0.3	1	0	0
41.	Particle spectrometer, TI low-field helium magnetometer												
	a) cosmic rays with magnetometer	55a		-2	III	I	III	III	IV	40	575	0	12
42.	Survey rate meter, TI low-field helium magnetometer												
	a) cosmic rays with magnetometer	55b			III	I	III	III	III	10.8	330	0	12
43.	Micrometeoroid and ejecta detector												
	a) micrometeoroid flux	56	2	1	IV	II	IV	V	III	27	1800	0	15
	b) trajectories, velocities and momenta of lunar ejecta	57			V	II	III	IV	III	27	1800	0	15

* 5 min during LEM descent

INSTRUMENT NO.	INSTRUMENT(S) OR EQUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF LUNAR SURFACE	ORIGIN, HISTORY, AGE OF EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN. 3)	POWER (WATTS)	TIME (MINUTES)	
44.	Susceptibility bridge (JPL-Bollin type, modified Mooney type)													
	a) susceptibility in situ	58		2	I	I	II	IV	II	0.7	18	0	10	
	b) anisotropy in susceptibility	61			I	I	I	II	IV	0.7	18	0	12	
45.	TI low-field helium magnetometer													
	a) magnetic field: vertical and horizontal components, vector sum and direction	59		-5	I	I	III	IV	IV	6.8	230	0	5	
	b) magnetic field gradient: vertical and horizontal components	60			II	I	II	III	III	6.8	230	0	20	
	c) magnetic field: diurnal and secular variations of vertical and horizontal components, vector sum and direction at 1 point, MHD waves	62			III	I	III	II	III	9	250	0	12	
	y) 45a) and 45b)		2		I	I	III	IV	IV	6.8	230	0	20	
					II	I	II	III	III	6.8	230	0	20	
	z) 45b) and 45c)		2		II	I	II	III	III	9	250	0	32	
					III	I	III	II	III	9	250	0	32	
46.	4 electrodes, voltmeter, cables													
	a) resistivity in situ (passive)				I	II	II	III	II	14	380	0	15	
47.	ac/dc, pulse current source, 4 electrodes, voltmeter, cables													
	a) resistivity in situ (active)			-4	I	II	II	III	II	15	400	0	15	
	b) anisotropy in resistivity				I	I	I	II	III	17	430	0	45	
	y) 47a) and 47c)		2		I	II	II	III	II	15	400	0	30	
					I	II	II	III	II	15	400	0	30	
	z) 47b) and 47c)		2		I	I	I	II	III	17	430	0	60	
					I	II	II	III	II	17	430	0	60	
	c) electrical transients in situ			1	I	II	II	III	II	15	400	0	15	
49.	2 electrodes, voltmeter, cables													
	a) spontaneous polarization in situ	64		1	I	II	II	III	II	10	300	0	15	
50.	TI low-field helium magnetometer, 4 electrodes, voltmeter, cables													
	a) correlation of E and H: short term 1 point	70		-2	I	I	II	III	II	20.5	610	0	20	
	b) correlation of E and H: long term 1 point	71			I	I	II	III	II	22.7	630	0	20	
51.	Cal Tech portable refraction seismic system, chemical source, 2 electrodes, voltmeter, cables													
	a) seismic-electrics	69		1	I	I	I	II	I	42	950	0	75	
52.	Visual observation													
	a) electrostatics	72b		-2	V	IV	IV	III	I	0	0	0	2	
53.	Charged dust detector													
	a) electrostatics	72a			III	III	III	IV	I	2	70	0	3	
56.	Quartz gravity meter													
	a) gravity	75		1	II	I	III	V	IV	7	450	0	5	

INSTRUMENT NO.	INSTRUMENT(S) OR EQUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF LUNAR SURFACE	ORIGIN, HISTORY, AGE OF EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN.³)	POWER (WATTS)	TIME (MINUTES)
57.	Gradiometer												
	a) gravity gradient	76		1	II	I	III	IV	III	5	430	0	5
58.	ITT-Lamont seismometer												
	a) tidal gravity	74b	3	-4	I	I	II	IV	V	37	1600	0	12
	b) seismicity and long-period noise	78b			II	II	III	IV	V	37	1600	0	12
	c) short-period noise	77b			II	I	IV	III	II	37	1600	0	12
55.	Tidal gravity meter												
	a) tidal gravity	74a			II	I	II	IV	V	33	1900	0	10
59.	55. and 60.		2		II	I	II	IV	V	48	2100	0	20
					II	I	IV	III	II	48	2100	0	20
60.	Cal Tech short-period seismometer												
	a) short-period noise	77a			II	I	IV	III	II	15	200	0	10
61.	Cal Tech portable refraction seismic system, mechanical source												
	a) active seismic: very short range	79		2	I	II	III	II	I	32	650	0	60
	b) soil depth or dust thickness	101b			II	III	III	V	I	32	650	0	20
62.	Cal Tech portable refraction seismic system, chemical source												
	a) active seismic: long range	80		1	I	I	II	V	IV	37	1100	0	60
63.	Platinum resistance element, resistance bridge												
	a) landing gear temperature	81		1	V	II	II	IV	II	0.5	4	0.015	2
64.	Copper-constantan thermocouple, sensor and reference units, millivoltmeter series circuit												
	a) boot temperature	82		1	IV	III	III	III	II	0.5	4	0	2
65.	Platinum resistance loop												
	a) surface temperature	83		1	III	III	V	IV	II	0.2	2	0	12
66.	Thermal conductivity probe												
	a) subsurface temperature	84	3	1	I	II	V	V	II	0.4	4	0	15
	b) subsurface thermal conductivity	86			I	III	IV	IV	II	0.4	4	0	15
	c) subsurface thermal diffusivity	88			I	II	IV	IV	II	0.4	4	0	15
67.	Thermal conductivity probe (landing gear)												
	a) landing site surface thermal conductivity	85		1	II	III	IV	IV	II	0.4	4	1	5
68.	Thermal conductivity probe, string of 6 platinum resistance thermometers, flexible tool w/impact-rotary impact components												
	a) subsurface heat flow	90		1	I	II	IV	V	V	32.8	430	0	40
69.	Modified flash radiometer												
	a) surface thermal diffusivity	87		1	I	III	IV	IV	II	5	1700	0	15
70.	Radiometric heat flow meter												
	a) surface heat flow	89		1	II	I	III	V	III	0.7	12	0	15

Instrument No.	Instrument(s) or Equipment Item(s)	Measurement No. (Cross Ref. to App. F)	Compiled Group Size (IGR)	Group Size (IGS)	Hazards	Trafficability	Lunar Basing	Origin, History, Age of Lunar Surface	Origin, History, Age of Earth - Moon System	Weight (Lbs.)	Volume (In.³)	Power (Watts)	Time (Minutes)	
72.	Line source pressure gauge, flexible tool w/impact-rotary impact components													
	a) subsurface interstitial gas pressure	92		1	II	I	IV	IV	III	34.5	450	0	40	
73.	Reflectance radiometer													
	a) surface emittance and reflectance (IR)	93	3	1	II	I	III	IV	II	8	150	0	15	
	b) surface reflectance (UV)	18			II	I	II	IV	II	8	150	0	15	
	c) surface reflectance (visible)	19			IV	I	II	IV	II	8	150	0	15	
74.	Maps, theodolite w/tripod													
	a) position of LEM by resection	94		1	II	II	II	II	II	9.6	750	0	15	
75.	Hand camera w/mil scale, level indicator, film, night stadia target on LEM													
	a) distance from LEM of sample sites and SIP	95a		2	II	V	V	V	IV	5.4	98	3	3	
	b) elevation relative to LEM of sample sites and SIP	97b			I	V	V	V	III	5.4	98	3	3	
76.	Tracking transducer on LEM TV camera													
	a) distance from LEM of sample sites and SIP	95b	3	1	II	II	II	II	II	4.5	150	10	0	
	b) azimuth at LEM of sample sites and SIP	96a			IV	II	V	V	III	4.5	150	10	0	
	c) elevation relative to LEM of sampling sites and SIP	97a			I	II	II	II	II	4.5	150	10	0	
79.	Photo transit w/tripod													
	a) elevation relative to LEM of sampling sites and SIP	97c		1	I	V	V	V	III	15	3300	0	18	
80.	Calipers, ruler, spring scale, flexible tool w/impact-rotary impact components													
	a) bulk density of soil or dust	99b		1	I	I	V	IV	I	34	440	0	10	
81.	Staff													
	a) soil depth or dust thickness	101a		2	V	IV	III	III	I	2	9	0	2	
	b) penetration resistance	102b			V	IV	II	III	I	2	9	0	2	
82.	Flexible tool w/impact-rotary impact components													
	a) soil depth or dust thickness	104c		1	I	I	III	IV	I	32	420	0	25	
83.	Vane shear tester													
	a) shear strength	103a		1	I	I	V	II	I	6	40	0	15	
84.	Direct shear tester, flexible tool w/all components													
	a) shear strength	103b		1	I	I	V	II	I	43	1120	0	60	
85.	Surveyor soil mechanics device (modified w/frame, anchors)													
	a) shear strength	103c		2	I	V	IV	II	I	28	1000	0	20	
	b) bearing strength	105a			II	V	V	II	I	28	1000	0	20	
86.	Penetrometer on staff													
	a) penetration resistance	102a		1	III	V	IV	II	I	2.5	20	0	2	
87.	Harvard miniature compaction apparatus (hammer, cylinder)													
	a) compaction	104		1	I	II	V	I	I	4	200	0	30	

INSTRUMENT NO.	INSTRUMENT(S) OR EQUIPMENT ITEM(S)	MEASUREMENT NO. (CROSS REF. TO APP. F)	COMPILED GROUP SIZE (IGR)	GROUP SIZE (IGS)	HAZARDS	TRAFFICABILITY	LUNAR BASING	ORIGIN, HISTORY, AGE OF: LUNAR SURFACE	ORIGIN, HISTORY, AGE OF: EARTH - MOON SYSTEM	WEIGHT (LBS.)	VOLUME (IN.³)	POWER (WATTS)	TIME (MINUTES)	
88.	Hand camera (special lens)													
	a) bearing strength	105b		2	IV	IV	III	I	I	5.3	90	0	2	
	b) stratigraphic elements of soil	107b			II	II	V	V	I	5.3	90	0	5	
89.	Soil sampling tube (sampling package)													
	a) soil density	99c		1	I	I	V	IV	I	0	0	0	5	
90.	Tethered sphere													
	a) penetration resistance	102c		1	IV	II	I	I	I	2	85	0	2	
91.	Visual observation, hand lens, hand camera (w/special lens)													
	a) microstructures of soil or dust	106a		1	II	IV	III	V	I	5.9	92	0	15	
92.	Visual observation, hand lens, hand camera (w/special lens), flexible tool w/all components													
	a) microstructures of soil or dust	106b		2	I	IV	IV	V	I	43.3	610	0	45	
	b) stratigraphic elements of soil	107a			I	I	V	V	I	43.3	610	0	45	
93.	Visual observation (sampling package): effects of thermal cycling	35		1	III	III	IV	IV	II	0	0	0	3	
94.	Visual observation (sampling package): sintering	36		1	III	III	IV	V	II	0	0	0	3	
95.	Line source pressure gauge													
	a) surface interstitial gas pressure	91	2	-2	III	I	IV	IV	III	2.5	25	0	35	
	b) vacuum outgassing	37b			III	I	IV	IV	III	2.5	25	0	35	
96.	Visual observation (sampling package): vacuum outgassing	37a			III	II	IV	IV	III	0	0	0	3	
97.	Erosion particle movement sampler: transportation	31a		-2	IV	III	IV	V	III	1	35	0	10	
98.	Visual observation (sampling package): transportation	31b			IV	III	III	IV	II	0	0	0	3	
99.	Visual observation (sampling package): angle of repose	28b		-2	III	III	III	III	II	0	0	0	1	
100.	Inclinometer: angle of repose	28a			IV	IV	IV	IV	II	0.5	10	0	2	
101.	Visual observation (sampling package): erosion	30		1	IV	IV	IV	V	III	0	0	0	2	
102.	Visual observation (sampling package): radiation damage (discoloration)	33		1	III	II	V	IV	IV	0	0	0	3	
103.	Visual observation (sampling package): micrometeorite accretion	34		1	II	II	V	V	V	0	0	0	3	
104.	Visual observation (sampling package): localization of ore and its genesis	17		1	II	II	IV	V	IV	0	0	0	10	
105.	Visual observation (sampling package): mineral identification	1		1	I	II	IV	V	IV	0	0	0	16	
106.	Visual observation (sampling package): rock color	6		1	II	III	II	IV	III	0	0	0	8	
107.	Visual observation (sampling package): soil or dust color	100		1	II	II	II	IV	I	0	0	0	5	

APPENDIX G

COMPUTER EVALUATION PROGRAM

APPENDIX G

COMPUTER EVALUATION PROGRAM

A. DETAILS OF COMPUTER EVALUATION PROGRAM

A Control Data 1604 computer was used in the evaluation program. Its choice was based on its storage capacity, speed, availability, and cost.

Functions of the computer evaluation program were outlined in Chapter VI of Part II. In general, the program selects combinations of instruments and related measurements from those listed in Appendix F for which the total scientific figures-of-merit are a maximum within the mission constraints.

The evaluation program consists of two computer programs. The first serves to prepare and record on magnetic tape the data input for the second program, which performs the operations specified in Chapter VI. The computer time required to execute the first program is approximately 2 min. For the second program, 3 to 5 min are required, depending upon special instructions which will be discussed subsequently.

First Program

The first computer program was designed primarily to facilitate executing the main or second program. The function of the first program is to accept the input data shown in Appendix F and to convert this data to a form most easily handled by the second program. The output of the first program is independent of the problem objectives or constraints. Instead, it reflects only the "instrumentation requirements" and "value ratings" for each measurement in Appendix F. The measurement ratings shown in Appendix F are indications of the category into which each measurement was rated for each problem area. The first program thus assigns the proper value to the categories indicated. It was noted in Chapter VI that for this study

$$R_I = 0, \; R_{II} = 1, \; R_{III} = 3, \; R_{IV} = 10, \text{ and } R_V = 20$$

The first program also was designed to handle special-case problems such as those discussed in the following paragraphs.

The data inputs to the evaluation program included in Appendix F are measurements listed in subgroups under one or a group of instruments.

It should be noted that one or more members of a subgroup can logically be included in a feasible system. Furthermore, additional members of a subgroup can be included with no additional instrumentation requirements. The additional time required by the astronaut to perform the additional measurements, however, must be considered. Hence, the first program was designed to construct all possible combinations of the members of the subgroup so that all of these combinations have the same instrumentation requirements but different time requirements and ratings. The input to the second program, therefore, is a list of all measurements listed in subgroups along with all combinations of these measurements with their total requirements and ratings. For example, consider measurements No. 27A, 27B and 27C in Appendix F. The total number of combinations of these three measurements is $2^n - 1 = 7$, i.e., the three original plus four combinations thereof. The characteristics of these combinations are shown below.

	WGT	VOL	POW	TIME	HAZ	TRAFF	L. B.	L. S.	SYS
27A	13.20	690.0	15.0	15.0	0	0	1	1	1
27B	13.20	690.0	15.0	15.0	3	1	10	10	3
27C	13.20	690.0	15.0	15.0	3	0	0	1	1
27AB	13.20	690.0	15.0	30.0	3	1	11	11	4
27AC	13.20	690.0	15.0	30.0	3	0	1	2	2
27BC	13.20	690.0	15.0	30.0	7	1	10	11	4
27ABC	13.20	690.0	15.0	45.0	6	1	11	12	5

This list of measurements and their possible combinations henceforth will be referred to as a family containing $2^n - 1$ members. The second program is instructed to include no more than one member of a given family in any postulated set. This is accomplished in the output of the first program by specifying a MIN and MAX which specify the first and last members of a given family respectively.

There is another use for this "family" concept wherein only one member of a given family should be included in a postulated system. For instance, whenever a given measurement could be performed by more than one instrument (or when measurements overlap sufficiently so that only one could be logically considered within a set of instruments), the second program would be so instructed by the output of the first. For example, consider measurements No. 99 and No. 100 from Appendix F, each of which is designed to obtain a measure of angle of repose on the lunar surface. Measurement No. 99 assumes a trained astronaut visually observing and estimating the angles of repose, whereas No. 100 specifies a more precise measurement. The two are overlapping and only one should be included in any postulated set of measurements to be performed.

It was not always feasible to avoid obtaining some duplication of instrumentation or overlapping of measurements. In such cases, the results had to be reviewed and a choice made between the duplicating or overlapping measurements. The net effect of this deficiency is minor. For example, consider any of the combinations in the sample output in Section B. A Jacob's staff is included twice, once by itself (No. 184 JS [81AB]) and once with a penetrometer (No. 191 JS/PENETROMETER [PENETRAT RESIST]). Such duplications are readily identifiable and can be corrected easily. For example, the Jacob's staff with penetrometer would be selected since it could duplicate the function of a simple Jacob's staff.

These situations are specified in the input data to the first program by the column labeled "Group Size." For instance, the first example above, No. 27, was denoted as having a group size of 3. The condition illustrated in the second example was handled by specifying a group size of -2. The minus sign indicates that no combinations of the two possible measurements were to be generated by the first program.

The first program also is designed to cope with another problem. Some measurements listed under an instrument group can be performed with no additional time requirements; hence, it is justifiable to sum the figures-of-merit of these measurements and instruct the computer to consider the characteristics of the sum as a single measurement. As an example, consider instrument No. 17 in Appendix F. A descent camera could be used for measuring (1) the orientation of topographic highs and lows, (2) areal extent of topographic highs and lows, (3) planar shape of topographic highs and lows, and (4) topographic mapping. The first program effectively sums the figures-of-merit of the above measurements and writes on magnetic tape the sum of the specifications as a single measurement. This is illustrated below.

	WGT	VOL	POW	TIME	HAZ	TRAFF	L. B.	L. S.	SYS
17A	9	550	75	0	1	10	3	10	1
17B	9	550	75	0	1	3	10	10	1
17C	9	550	75	0	1	3	1	10	1
17D	9	550	75	0	20	20	20	20	10
17	9	550	75	0	23	36	34	50	13

Other examples from Appendix F are No. 24, 29 and 30. The measurements are listed separately in the appendix because each was individually rated and classified by the appropriate study group.

In summary, the first program accepts the data input as shown in Appendix F, performs the operations as described and writes on magnetic tape the resulting specifications of the measurements and combinations of measurements required as inputs for the second program.

A step-by-step account of the operations of the first program is presented below.

(1) The computer reads the first punched data card which is an identification card containing identifying features of the input data; for example,
APOLLO INSTRUMENTATION MATRIX ANALYSIS 0, 1, 3, 10, 20.

(2) The above identification is printed out and also written on magnetic tape.

(3) The computer reads the next data card on which is punched the selected ratios R_0, R_1, R_2, R_3, and R_4.

(4) The computer then reads the following punched data card which contains the specifications and ratings of a measurement, including those shown below:

(a) ID(I), the index number of the measurement as shown in Appendix F

(b) IDD(I), the index letter as shown in Appendix F

(c) IGR(I), a number that identifies the number of measurements which follow, for which the scientific figures-of-merit are to be added to that of the first measurement, as discussed previously

(d) IGS(I), a number indicating the group size (positive group sizes indicating that a family is to be constructed from the number of measurements specified, an example of which was presented previously)

(e) HAZ(I), a rating, I, II, III, IV, or V, which specifies the category into which the particular instrument was classified, as previously described, for the problem area "hazards"

(f) TRAFF(I), a number specifying the classification for trafficability

(g) L. B. (I), the classification under lunar basing

(h) L. S. (I), the classification under lunar surface, history, origin, age

(i) SYS(I), the classification under earth-moon system history, age, origin

(j) WGT(I), the weight of the associated instrumentation

(k) VOL(I), the associated volume

(l) POW(I), the required power

(m) TIME(I), the astronaut's time required to execute the measurement being considered

(5) The computer then replaces the number designating the category of classification by the proper ratio R_k as specified on the first data input card.

(6) If the group number IGR(I) is greater than 0, the scientific figures-of-merit of the following IGR(I) measurements are summed with that just read. If IGR(I) is equal to 0, the computer proceeds to the next step.

(7) If the group size IGS(I) is less than 0, the number corresponding to its absolute value denotes the number of measurements which are to be considered as a family but from which no combinations are to be constructed. If, however, the group size is greater than 0, its value specifies the total number of measurements that, with all their possible combinations, are to be considered a family, from which only one could be selected for any given combination of measurements. The MIN, the number of the first member of the family, and MAX, the last member of that family, also are determined.

(8) For each measurement or combination of measurements generated in the above steps, the following data are recorded on magnetic tape:

(a) W(I)

(b) V(I)

(c) P(I)

(d) T(I)

(e) MIN(I)

(f) MAX(I)

(g) The index name as shown in Appendix F

(h) An abbreviated form of the instrument name and the associated measurements

(i) HAZ(I), the hazard rating of the measurement or the accumulated hazard ratings of the combined measurements

(j) TRAFF(I), the accumulated trafficability rating

(k) L. B. (I), the accumulated lunar basing rating

(l) L. S. (I), the accumulated lunar surface history, origin rating

(m) SYS(I), the accumulated earth-moon system history, origin rating

(9) The computer then returns to Step 4 and repeats the preceding operations until all punched data cards have been read. To facilitate quick checking of the correctness and the completeness of the input data, each time the computer reads an input data card for a particular measurement, it prints out the specifications of that measurement on the associated printer.

(10) After the program has processed all the input data cards and written on tape the information described above, it prints out via the printer the total number of measurements or instruments, or combinations thereof, that were generated.

Second Program

Inputs to the second program consist of: (1) the magnetic tape prepared by the first program; (2) the problem constraints - power, weight, volume, and astronaut time allocations for the specific mission being considered; (3) the weighting factors C_k for the five areas; and (4) special instructions to the second program such as the total number of measurements and their combinations to be read from the tape.

The total number of measurements and combinations of measurements resulting from this study was 216. Even if no more than one member of a family is included in a combination, the total number of possible combinations is considerably in excess of 10^{30}, which would take the fastest computers many years to generate. Hence, some basis for considering only the more feasible of the possible combinations must be incorporated into the system-postulation function of the computer program. There are obviously many possible ways to accomplish this, and the more realistic the selection process, the fewer the number of unrealistic combinations the program would have to evaluate. For instance, all of the possible combinations which contain so many measurements that the problem constraints are exceeded are deemed unrealistic and not worthy of evaluation in the program. Similarly, all of those possible combinations which contain so few measurements that the requirements of the combination are considerably less than those available are not worthy of evaluation. Furthermore, the generation-evaluation process can be facilitated by defining for each measurement or combination of measurements a figure-of-merit which reflects both the "value" and the "cost" of that measurement. This figure-of-merit is not used as a basis for evaluation but solely as a means of preferentially selecting combinations of instruments yielding the most "value per cost". Several such figures-of-merit were considered during this study, the most realistic of which is defined by

$$\text{NORMALIZED } S(M) \qquad \frac{S(M)}{\frac{T}{T_{max}} + \frac{W}{W_{max}} + \frac{V}{V_{max}} + \frac{P}{P_{max}}}$$

This normalized figure-of-merit, therefore, reflects the value or scientific figure-of-merit and the instrumentation requirements expressed as fractions of the instrument allocations. The second program, then, ranks all of the measurements in the input data on the basis of their normalized figure-of-merit and begins generating feasible combinations of measurements by first considering those measurements having the highest value per cost. This ordering scheme by no means eliminates those measurements with low normalized figures-of-merit; however, the frequency of their being included in a feasible combination is considerably less than that for measurements with high normalized figures-of-merit.

Results of the computer evaluation program tend to verify the ordering scheme in that the combinations with the highest total scientific figures-of-merit consist primarily of measurements that rate close to the top in normalized figure-of-merit. This is indicated in the results by the relatively low average rank number of all of the top 100 combinations. The total number of combinations considered by the program is generally of the order of 1,000,000.

The measurements, requirements and specifications written on the magnetic tape are direct inputs to the second program. The first printed output of the program is the calculated figures-of-merit and normalized figures-of-merit for each of the 216 measurements. The computer then ranks the instruments (measurements) according to the value of its normalized figure-of-merit. The results are then printed out in order of rank, together with the specifications and requirements of the measurement. The printed output of a sample run is shown in Section B.

The first combination of measurements evaluated by this program is determined by scanning down the ranked measurement list, beginning from the top and including all "legal" measurements for which the accumulated instrumentation requirements do not exceed the constraints. "Legal" measurements are those which have not been eliminated as candidates for a given combination for any of the reasons discussed previously, e.g., those members of a measurement family that already have been included in the combination, etc. Once this first combination has been determined and its characteristics evaluated, the computer prints out the following information:

- Total accumulated scientific figure-of-merit
- Total weight of the instrumentation associated with the selected measurements
- Total volume requirements of the combination
- Total power requirements
- Total astronaut's time required to execute the included measurements
- Average rank of the combination
- Number of measurements included in the combination
- Instrument or measurement number of each measurement included in the combination

The program then executes a specified routine of dropping various measurements included in the first combination and adding lower ranking ones for which the instrumentation and time requirements are compatible with the constraints. Each measurement is individually dropped from the first combination, then measurements are dropped in pairs, etc., until all of the measurements included in the first combination are excluded simultaneously. There are infinitely many patterns for specifying the order of selecting combinations, but none can be defended realistically as being the single best pattern. The pattern briefly described above was used in this study and is considered to be adequate.

Experience showed that in most cases it is unnecessary to exclude all members of the first combination in selecting feasible systems to be considered and evaluated. In fact, the results of the computer evaluation program show that rarely did any of the 100 combinations with the highest figures-of-merit differ from the first combination by more than four or five measurements. To insure that this was so, the program was instructed generally to drop at most 10 or 15 measurements from the first combination simultaneously and to consider the remaining possible combinations.

Once the generation-evaluation loop has been completed, the total number of combinations considered and the total number that fell within the constraints are printed out. Details of the first combination are printed out, as well as the specifications of the 100 measurements with the highest total scientific figures-of-merit.

Final output of the computer evaluation program is intended to summarize the results of the entire evaluation program. This output specifies the number of times each instrument and the associated measurement(s) were included in the top 100 combinations.

A step-by-step account of the operations of the second program is outlined below.

(1) The program first instructs the computer to read from the magnetic tape the input data prepared by the first program.

(2) The computer calculates the scientific figure-of-merit S(I) as follows:

$$S(I) = C_1 \times HAZ(I) + C_2 \times TRAFF(I) + C_3 \times L.B.(I) + C_4 \times L.S.(I) + C_5 \times SYS(I)$$

(3) The normalized figure-of-merit NORMS(I) is computed as follows:

$$\text{NORMS(I)} = \frac{S(I)}{\dfrac{T}{T_{max}} + \dfrac{W}{W_{max}} + \dfrac{V}{V_{max}} + \dfrac{P}{P_{max}}}$$

(4) Results of the above computations then are printed out along with the following data:

(a) INST, the instrument number of computer name for a given instrument (and measurement or measurements)

(b) INDEX, the index number, the inverted form of the input data

(c) WGT, instrument weight

(d) VOL, instrument volume

(e) POW, power required

(f) TIME, astronaut's time required to set up apparatus and execute the specified measurements

(g) S(I), scientific figure-of-merit

(h) NORMS(I), normalized figure-of-merit

(i) MIN, instrument number which designates the first member of the family of each instrument

(j) MAX, instrument number which designates the last member of the family of the I'th instrument

(5) The computer ranks the measurements according to the NORMS(I)'s.

(6) The above is followed by a printed output of

(a) RANK, the number denoting the relative value of an instrument's normalized figure-of-merit, i.e., with the highest being 1 and the lowest being NMAX

(b) INST

(c) S (I)

(d) NORMS (I)

(e) TIME

(f) WGT

(g) VOL

(h) POW

(7) The computer begins the process of generating the first feasible combination of measurements. It does this by starting at the top of the ranked list of measurements and defining the accumulated STO, TTO, PTO, WTO, and VTO equal to the S(I), T(I), P(I), and W(I) of the highest ranking measurement, respectively. The computer then considers each measurement ranking below the top ranking one and, if it is a legal candidate as defined previously and if its time and hardware requirements, when added to the accumulated totals, do not exceed the constraints, the measurement is included in the first combination. In practice, often about 30 or 40 measurements, and instruments, have been selected for the first combination; those remaining of the original 216 are either not legal candidates or the requirements, such as time, weight or volume, when added to the sums of those already selected, are too great.

(8) The computer stores in its memory all pertinent facts about the first combination.

(9) The computer drops the lowest ranking instrument included in the first combination and searches the lower ranking instruments for all possible combinations that fall within the constraints.

Note: Each time a combination falls within the constraints, facts about that combination are stored. This process continues until JMAX combinations have been stored in the memory. JMAX cannot exceed 100. Following this, the STO for each new combination is compared with the lowest ranking stored STO. If the new STO is greater, its specifications and characteristic values replace those previously stored.

(10) The computer proceeds by adding the instrument just dropped, dropping the member of the first combination that ranks just above the one previously dropped and again searching the lower ranking instruments for other combinations falling within the constraints.

(11) Step 10 is repeated until the top ranking instrument in the first combination has been dropped and all lower ranking instruments have been considered for new combinations.

(12) The computer re-establishes the first combination, drops the two lowest ranking instruments included in the first combination and again searches all lower ranking instruments for new combinations that fall within the constraints.

(13) The computer adds the lowest ranking instrument and drops from the list the instrument ranking next to the lowest and repeats the above searching process.

(14) The above process is repeated until the two top ranking instruments have been dropped and the remaining instruments searched.

(15) The computer re-establishes the first combination, drops the bottom and third-from-bottom ranking instruments and scans the lower ranked ones.

(16) The computer adds the third-from-bottom and drops the fourth-from-bottom and searches.

(17) The above process is repeated until the top and the bottom instruments have been dropped from the first combination.

(18) The computer is then instructed to re-establish the first combination and drop the bottom three instruments.

(19) The computer stair-steps the three instruments up from the lowest ranking until the three top ranking instruments have been dropped.

(20) Step 18 is repeated.

(21) The computer follows by stair-stepping the third-from-bottom ranking instrument up until the two bottom ranking instruments and the top instrument have been dropped.

(22) The computer repeats Step 18 but drops the bottom four instruments.

(23) The computer repeats Step 19 except it stair-steps all four instruments until the top four have been dropped.

(24) Step 22 is repeated.

(25) The computer repeats Step 21 except it stair-steps the fourth-from-bottom until the bottom three and the top instrument have been dropped.

(26) The computer repeats Steps 22 through 25 each time dropping one additional instrument from the first combination, i.e., by replacing four with five, six, seven, etc., in the above steps. This interaction is continued until some selected number of instruments (MOST) has been dropped.

(27) The computer prints the output of the total number of combinations considered during the above operations and those that fell within the constraints.

(28) The computer also prints the output of the NUMB (input data) combinations, instrument numbers and names, with the highest total scientific figure-of-merit, STOT, along with the pertinent facts about each, including:

(a) STOT, total scientific figure-of-merit

(b) WTOT, total weight of the combination

(c) TTOT, total astronaut time required to set up and perform all measurements in the combination

(d) PTOT, total power requirements

(e) VTOT, total volume requirements

(f) AVG, average rank of the combination (a measure of the validity of ranking by NORMS)

(g) NOI, number of instruments included in the combination

(h) COMB, combination number, beginning with the first

(29) Also printed out is the output of the remaining (JMAX-NUMB) combinations along with the pertinent facts (in this print-out, only instrument number is printed in order to speed up the printout procedure).

(30) Final step of the second program is to print the output of the number of times each instrument was included in the JMAX top ranking combinations along with the instrument number and name.

B. SAMPLE OUTPUT OF COMPUTER PROGRAM

1. Sample Output of First Program

APOLLO INSTRUMENTATION MATRIX ANALYSIS B 0, 1, 3, 10, 20

ID	GS	HAZ	TRAF	L.B.	L.S.	SYS	WGT	VOL	POW	TIME
1	1	3.0	10.0	10.0	10.0	3.0	2.6	11.0	0	8.0
2	1	1.0	1.0	0	10.0	0	2.0	40.0	0	10.0
3A	2	3.0	10.0	10.0	10.0	1.0	.5	10.0	0	4.0
3B	2	10.0	10.0	3.0	20.0	1.0	.5	10.0	0	5.0
4	1	20.0	20.0	10.0	10.0	3.0	11.0	560.0	75.0	10.0
6A	6	1.0	1.0	3.0	20.0	10.0	10.3	120.0	0	30.0
6B	6	1.0	1.0	3.0	20.0	10.0	10.3	120.0	0	30.0
6C	6	3.0	10.0	10.0	20.0	10.0	10.3	120.0	0	25.0
6D	6	1.0	1.0	1.0	20.0	10.0	10.3	120.0	0	10.0
6E	6	1.0	10.0	10.0	20.0	3.0	10.3	120.0	0	15.0
6F	6	0	0	10.0	10.0	10.0	10.3	120.0	0	10.0
7A	2	0	3.0	10.0	20.0	10.0	.6	2.0	0	8.0
7B	2	0	0	10.0	20.0	10.0	.6	2.0	0	6.0
8A	3	3.0	3.0	3.0	10.0	10.0	.6	2.0	0	8.0
8B	3	1.0	3.0	3.0	10.0	10.0	.6	2.0	0	8.0
8C	3	0	3.0	3.0	10.0	1.0	.6	2.0	0	10.0
9	1	3.0	10.0	3.0	1.0	1.0	0	0	0	2.0
10	1	1.0	1.0	3.0	10.0	20.0	17.0	720.0	0	12.0
11A	2	1.0	3.0	10.0	10.0	3.0	3.0	22.0	0	4.0
11B	2	0	0	1.0	10.0	10.0	3.0	22.0	0	8.0
12	1	10.0	10.0	10.0	10.0	3.0	16.3	640.0	75.0	20.0
13	1	10.0	20.0	10.0	10.0	1.0	17.3	660.0	75.0	10.0
14	1	10.0	20.0	20.0	10.0	1.0	1.0	20.0	0	10.0
17	1	23.0	36.0	34.0	50.0	13.0	9.0	550.0	75.0	0
18	1	20.0	20.0	20.0	10.0	1.0	5.8	100.0	0	5.0
19	1	0	3.0	10.0	10.0	10.0	17.6	1200.0	60.0	15.0
20A	2	0	0	3.0	3.0	3.0	2.0	40.0	5.0	15.0
20B	2	3.0	1.0	1.0	3.0	1.0	2.0	40.0	5.0	15.0
21	1	0	0	10.0	1.0	1.0	10.0	860.0	200.0	10.0
22	1	0	0	10.0	10.0	10.0	33.0	360.0	25.0	15.0
23A	2	0	0	3.0	3.0	3.0	12.0	1700.0	4.0	15.0
23B	2	1.0	0	0	1.0	1.0	12.0	1700.0	4.0	15.0
24	1	3.0	1.0	4.0	6.0	13.0	24.0	1740.0	0	15.0
25	1	0	0	3.0	3.0	3.0	5.2	560.0	0	15.0
26	1	0	1.0	10.0	1.0	1.0	30.3	870.0	0	20.0
27A	3	0	0	1.0	1.0	1.0	13.2	690.0	15.0	15.0
27B	3	3.0	1.0	10.0	10.0	3.0	13.2	690.0	15.0	15.0
27C	3	3.0	0	0	1.0	1.0	13.2	690.0	15.0	15.0
28A	3	1.0	1.0	4.0	11.0	11.0	15.0	860.0	27.0	15.0
28B	3	3.0	1.0	3.0	3.0	3.0	15.0	860.0	27.0	15.0
28D	3	1.0	0	0	1.0	1.0	15.0	860.0	27.0	15.0
29	1	21.0	1.0	15.0	24.0	14.0	12.1	860.0	0	15.0
30	1	1.0	0	2.0	4.0	4.0	4.1	430.0	0	10.0
31A	2	0	3.0	3.0	1.0	1.0	26.1	950.0	0	20.0
31B	2	1.0	1.0	3.0	10.0	0	26.1	950.0	0	20.0
32	1	1.0	1.0	10.0	3.0	0	9.0	120.0	0	10.0
33	-2	20.0	0	0	3.0	1.0	1.2	28.0	1.3	5.0
34	-2	10.0	0	0	3.0	1.0	1.5	1600.0	0	5.0
35	1	3.0	0	4.0	13.0	6.0	15.0	410.0	0	5.0
36A	1	10.0	0	11.0	2.0	2.0	1.8	82.0	0	5.0
36C	1	13.0	0	11.0	4.0	11.0	1.0	70.0	.1	0
37	1	30.0	0	20.0	13.0	4.0	31.0	325.0	0	5.0
38	1	11.0	0	4.0	4.0	3.0	2.0	60.0	0	10.0
39	1	20.0	10.0	10.0	3.0	3.0	.5	17.0	.0	10.0
40	1	20.0	0	10.0	0	0	.3	1.0	0	0

41	-2	3.0	0	3.0	3.0	10.0	40.0	575.0	0	12.0
42	-2	3.0	0	3.0	3.0	3.0	10.8	330.0	0	12.0
43	1	30.0	2.0	13.0	30.0	6.0	27.0	1800.0	0	15.0
44A	2	0	0	1.0	10.0	1.0	.7	18.0	0	10.0
44B	2	0	0	0	1.0	10.0	.7	18.0	0	12.0
45A	-5	0	0	3.0	10.0	10.0	6.8	230.0	0	5.0
45B	-5	1.0	0	1.0	3.0	3.0	6.8	230.0	0	20.0
45C	-5	3.0	0	3.0	1.0	3.0	9.0	250.0	0	12.0
45Y	-5	1.0	0	4.0	13.0	13.0	6.8	230.0	0	20.0
45Z	-5	4.0	0	4.0	4.0	6.0	9.0	250.0	0	32.0
46	1	0	1.0	1.0	3.0	1.0	14.0	380.0	0	15.0
47A	-4	0	1.0	1.0	3.0	1.0	15.0	400.0	0	15.0
47B	-4	0	0	0	1.0	3.0	17.0	430.0	0	45.0
47Y	-4	0	2.0	2.0	6.0	2.0	15.0	400.0	0	30.0
47Z	-4	0	1.0	1.0	4.0	4.0	17.0	430.0	0	60.0
47C	1	0	1.0	1.0	3.0	1.0	15.0	400.0	0	15.0
49	1	0	1.0	1.0	3.0	1.0	10.0	300.0	0	15.0
50A	-2	0	0	1.0	3.0	1.0	20.5	610.0	0	20.0
50B	-2	0	0	1.0	3.0	1.0	22.7	630.0	0	20.0
51	1	0	0	0	1.0	0	42.0	950.0	0	75.0
52	-2	20.0	10.0	10.0	3.0	0	0	0	0	2.0
53	-2	20.0	10.0	10.0	10.0	0	2.0	70.0	0	3.0
54	1	20.0	3.0	1.0	1.0	0	.5	70.0	0	1.0
56	1	1.0	0	3.0	20.0	10.0	7.0	450.0	0	5.0
57	1	1.0	0	3.0	10.0	3.0	5.0	430.0	0	5.0
58	-4	2.0	1.0	14.0	23.0	41.0	37.0	1600.0	0	12.0
55	-4	1.0	0	1.0	10.0	20.0	33.0	1900.0	0	10.0
59	-4	2.0	0	11.0	13.0	21.0	48.0	2100.0	0	20.0
60	-4	1.0	0	10.0	3.0	1.0	15.0	200.0	0	10.0
61A	2	0	1.0	3.0	1.0	0	32.0	650.0	0	60.0
61B	2	1.0	3.0	3.0	20.0	0	32.0	650.0	0	60.0
62	1	0	0	1.0	20.0	10.0	37.0	1100.0	0	60.0
63	1	20.0	1.0	1.0	10.0	1.0	.5	4.0	.0	2.0
64	1	10.0	3.0	3.0	3.0	1.0	.5	4.0	0	2.0
65	1	3.0	3.0	20.0	10.0	1.0	.2	2.0	0	12.0
66	1	0	5.0	40.0	40.0	3.0	.4	4.0	0	15.0
67	1	1.0	3.0	10.0	10.0	1.0	.4	4.0	1.0	5.0
68	1	0	1.0	10.0	20.0	20.0	32.8	430.0	0	40.0
69	1	0	3.0	10.0	10.0	1.0	5.0	1700.0	0	15.0
70	1	1.0	0	3.0	20.0	3.0	.7	12.0	0	15.0
72	1	1.0	0	10.0	10.0	3.0	34.5	450.0	0	40.0
73	1	12.0	0	5.0	30.0	3.0	8.0	150.0	0	15.0
74	1	1.0	1.0	1.0	1.0	1.0	9.6	750.0	0	15.0
75A	2	1.0	20.0	20.0	20.0	10.0	5.4	98.0	3.0	3.0
75B	2	0	20.0	20.0	20.0	3.0	5.4	98.0	3.0	3.0
76	1	11.0	3.0	22.0	22.0	5.0	4.5	150.0	10.0	0
79	1	0	20.0	20.0	20.0	3.0	15.0	3300.0	0	18.0
80	1	0	0	20.0	10.0	0	34.0	440.0	0	10.0
81A	2	20.0	10.0	3.0	3.0	0	2.0	9.0	0	2.0
81B	2	20.0	10.0	1.0	3.0	0	2.0	9.0	0	2.0
82	1	0	0	3.0	10.0	0	32.0	420.0	0	25.0
83	1	0	0	20.0	1.0	0	6.0	40.0	0	15.0
84	1	0	0	20.0	1.0	0	43.0	1120.0	0	60.0
85A	2	0	20.0	10.0	1.0	0	28.0	1000.0	0	20.0
85B	2	1.0	20.0	20.0	1.0	0	28.0	1000.0	0	20.0
86	1	3.0	20.0	10.0	1.0	0	2.5	20.0	0	2.0
87	1	0	1.0	20.0	0	0	4.0	200.0	0	30.0
88A	2	10.0	10.0	3.0	0	0	5.3	90.0	0	2.0
88B	2	1.0	1.0	20.0	20.0	0	5.3	90.0	0	5.0
89	1	0	0	20.0	10.0	0	0	0	0	5.0
90	1	10.0	1.0	0	0	0	2.0	85.0	0	2.0
91	1	1.0	10.0	3.0	20.0	0	5.9	92.0	0	15.0
92A	2	0	10.0	10.0	20.0	0	43.3	610.0	0	45.0
92B	2	0	0	20.0	20.0	0	43.3	610.0	0	45.0
93	1	3.0	3.0	10.0	10.0	1.0	0	0	0	3.0
94	1	3.0	3.0	10.0	20.0	1.0	0	0	0	3.0

95	-2	6.0	0	20.0	20.0	6.0	2.5	25.0	0	35.0
96	-2	3.0	1.0	10.0	10.0	3.0	0	0	0	3.0
97	-2	10.0	3.0	10.0	20.0	3.0	1.0	35.0	0	10.0
98	-2	10.0	3.0	3.0	10.0	1.0	0	0	0	3.0
99	-2	3.0	3.0	3.0	3.0	1.0	0	0	0	1.0
100	-2	10.0	10.0	10.0	10.0	1.0	.5	1.0	0	2.0
101	1	10.0	10.0	10.0	20.0	3.0	0	0	0	2.0
102	1	3.0	1.0	20.0	10.0	10.0	0	0	0	3.0
103	1	1.0	1.0	20.0	20.0	20.0	0	0	0	3.0
104	1	1.0	1.0	10.0	20.0	10.0	0	0	0	10.0
105	1	0	1.0	10.0	20.0	10.0	0	0	0	16.0
106	1	1.0	3.0	1.0	10.0	3.0	0	0	0	8.0
107	1	1.0	1.0	1.0	10.0	0	0	0	0	5.0

TOTAL NUMBER OF INSTRUMENTS = 216

2. Sample Output of Second Program

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 .6,1.5,1.5,.5,.5

APOLLO INSTRUMENTATION MATRIX ANALYSIS B 0, 1, 3, 10, 20

INST	INDEX	WGT	VOL	POW	TIME	S(I)	NORM FOM	MIN	MAX
1	1	2.60	11.00	0	8.00	54.50	496.43	1	1
2	2	2.00	40.00	0	10.00	12.50	95.00	2	2
3	3A	.50	10.00	0	4.00	53.50	1062.84	3	5
4	3B	.50	10.00	0	5.00	90.00	1452.44	3	5
5	3AB	.50	10.00	0	9.00	143.50	1322.87	3	5
6	4	11.00	560.00	75.00	10.00	171.50	525.45	6	6
7	6A	10.30	120.00	0	30.00	27.00	64.12	7	69
8	6B	10.30	120.00	0	30.00	27.00	64.12	7	69
9	6C	10.30	120.00	0	25.00	63.00	173.59	7	69
10	6D	10.30	120.00	0	10.00	24.00	127.31	7	69
11	6E	10.30	120.00	0	15.00	47.50	192.58	7	69
12	6F	10.30	120.00	0	10.00	25.00	132.62	7	69
13	6AB	10.30	120.00	0	60.00	54.00	70.14	7	69
14	6AC	10.30	120.00	0	55.00	90.00	126.45	7	69
15	6AD	10.30	120.00	0	40.00	51.00	94.91	7	69
16	6AE	10.30	120.00	0	45.00	74.50	125.11	7	69
17	6AF	10.30	120.00	0	40.00	52.00	96.77	7	69
18	6BC	10.30	120.00	0	55.00	90.00	126.45	7	69
19	6BD	10.30	120.00	0	40.00	51.00	94.91	7	69
20	6BE	10.30	120.00	0	45.00	74.50	125.11	7	69
21	6BF	10.30	120.00	0	40.00	52.00	96.77	7	69
22	6CD	10.30	120.00	0	35.00	87.00	181.55	7	69
23	6CE	10.30	120.00	0	40.00	110.50	205.64	7	69
24	6CF	10.30	120.00	0	35.00	88.00	183.64	7	69
25	6DE	10.30	120.00	0	25.00	71.50	197.01	7	69
26	6DF	10.30	120.00	0	20.00	49.00	160.77	7	69
27	6EF	10.30	120.00	0	25.00	72.50	199.76	7	69
28	6ABC	10.30	120.00	0	85.00	117.00	110.31	7	69
29	6ABD	10.30	120.00	0	70.00	78.00	88.02	7	69
30	6ABE	10.30	120.00	0	75.00	101.50	107.48	7	69
31	6ABF	10.30	120.00	0	70.00	79.00	89.15	7	69
32	6ACD	10.30	120.00	0	65.00	114.00	137.67	7	69
33	6ACE	10.30	120.00	0	70.00	137.50	155.16	7	69
34	6ACF	10.30	120.00	0	65.00	115.00	138.88	7	69
35	6ADE	10.30	120.00	0	55.00	98.50	138.39	7	69
36	6ADF	10.30	120.00	0	50.00	76.00	116.27	7	69
37	6AEF	10.30	120.00	0	55.00	99.50	139.79	7	69
38	6BCD	10.30	120.00	0	65.00	114.00	137.67	7	69
39	6BCE	10.30	120.00	0	70.00	137.50	155.16	7	69
40	6BCF	10.30	120.00	0	65.00	115.00	138.88	7	69
41	6BDE	10.30	120.00	0	55.00	98.50	138.39	7	69
42	6BDF	10.30	120.00	0	50.00	76.00	116.27	7	69
43	6BEF	10.30	120.00	0	55.00	99.50	139.79	7	69
44	6CDE	10.30	120.00	0	50.00	134.50	205.77	7	69
45	6CDF	10.30	120.00	0	45.00	112.00	188.08	7	69
46	6CEF	10.30	120.00	0	50.00	135.50	207.30	7	69
47	6DEF	10.30	120.00	0	35.00	96.50	201.37	7	69
48	6ABCD	10.30	120.00	0	95.00	141.00	119.81	7	69
49	6ABCE	10.30	120.00	0	100.00	164.50	133.20	7	69
50	6ABCF	10.30	120.00	0	95.00	142.00	120.66	7	69
51	6ABDE	10.30	120.00	0	85.00	125.50	118.33	7	69
52	6ABDF	10.30	120.00	0	80.00	103.00	102.75	7	69
53	6ABEF	10.30	120.00	0	85.00	126.50	119.27	7	69

54	6ACDE	10.30	120.00	0	80.00	161.50	161.10	7	69
55	6ACDF	10.30	120.00	0	75.00	139.00	147.19	7	69
56	6ACEF	10.30	120.00	0	80.00	162.50	162.10	7	69
57	6ADEF	10.30	120.00	0	65.00	123.50	149.15	7	69
58	6BCDE	10.30	120.00	0	80.00	161.50	161.10	7	69
59	6BCDF	10.30	120.00	0	75.00	139.00	147.19	7	69
60	6BCEF	10.30	120.00	0	80.00	162.50	162.10	7	69
61	6BDEF	10.30	120.00	0	65.00	123.50	149.15	7	69
62	6CDEF	10.30	120.00	0	60.00	159.50	207.17	7	69
63	6ABCDE	10.30	120.00	0	110.00	188.50	139.49	7	69
64	6ABCDF	10.30	120.00	0	105.00	166.00	128.37	7	69
65	6ABCEF	10.30	120.00	0	110.00	189.50	140.23	7	69
66	6ABDEF	10.30	120.00	0	95.00	150.50	127.88	7	69
67	6ACDEF	10.30	120.00	0	90.00	186.50	166.70	7	69
68	6BCDEF	10.30	120.00	0	90.00	186.50	166.70	7	69
69	6ABCDEF	10.30	120.00	0	120.00	213.50	145.48	7	69
70	7A	.60	2.00	0	8.00	34.50	356.22	70	72
71	7B	.60	2.00	0	6.00	30.00	407.64	70	72
72	7AB	.60	2.00	0	14.00	64.50	387.11	70	72
73	8A	.60	2.00	0	8.00	37.00	382.03	73	79
74	8B	.60	2.00	0	8.00	25.00	258.13	73	79
75	8C	.60	2.00	0	10.00	14.50	120.73	73	79
76	8AB	.60	2.00	0	16.00	62.00	326.53	73	79
77	8AC	.60	2.00	0	18.00	51.50	241.64	73	79
78	8BC	.60	2.00	0	18.00	39.50	185.33	73	79
79	8ABC	.60	2.00	0	26.00	76.50	249.88	73	79
80	9	0	0	0	2.00	38.50	1655.50	80	80
81	10	17.00	720.00	0	12.00	27.00	90.42	81	81
82	11A	3.00	22.00	0	4.00	32.00	480.75	82	84
83	11B	3.00	22.00	0	8.00	11.50	101.70	82	84
84	11AB	3.00	22.00	0	12.00	43.50	272.58	82	84
85	12	16.30	640.00	75.00	20.00	96.50	200.53	85	85
86	13	17.30	660.00	75.00	10.00	110.50	296.56	86	86
87	14	1.00	20.00	0	10.00	125.50	1012.67	87	87
88	17	9.00	550.00	75.00	0	274.50	1392.71	88	88
89	18	5.80	100.00	0	5.00	185.50	1831.36	89	89
90	19	17.60	1200.00	60.00	15.00	29.50	65.01	90	90
91	20A	2.00	40.00	5.00	15.00	7.50	38.19	91	93
92	20B	2.00	40.00	5.00	15.00	23.00	117.12	91	93
93	20AB	2.00	40.00	5.00	30.00	30.50	82.25	91	93
94	21	10.00	860.00	200.00	10.00	16.00	31.38	94	94
95	22	33.00	360.00	25.00	15.00	25.00	57.17	95	95
96	23A	12.00	1700.00	4.00	15.00	7.50	19.58	96	98
97	23B	12.00	1700.00	4.00	15.00	7.00	18.28	96	98
98	23AB	12.00	1700.00	4.00	30.00	14.50	26.01	96	98
99	24	24.00	1740.00	0	15.00	35.00	77.06	99	99
100	25	5.20	560.00	0	15.00	7.50	30.12	100	100
101	26	30.30	870.00	0	20.00	17.50	36.12	101	101
102	27A	13.20	690.00	15.00	15.00	2.50	7.62	102	108
103	27B	13.20	690.00	15.00	15.00	41.00	125.03	102	108
104	27C	13.20	690.00	15.00	15.00	19.00	57.94	102	108
105	27AB	13.20	690.00	15.00	30.00	43.50	86.59	102	108
106	27AC	13.20	690.00	15.00	30.00	21.50	42.80	102	108
107	27BC	13.20	690.00	15.00	30.00	60.00	119.44	102	108
108	27ABC	13.20	690.00	15.00	45.00	62.50	92.35	102	108
109	28A	15.00	860.00	27.00	15.00	24.50	66.59	109	115
110	28B	15.00	860.00	27.00	15.00	27.00	73.38	109	115
111	28D	15.00	860.00	27.00	15.00	7.00	19.03	109	115
112	28AB	15.00	860.00	27.00	30.00	51.50	94.96	109	115
113	28AD	15.00	860.00	27.00	30.00	31.50	58.08	109	115
114	28BD	15.00	860.00	27.00	30.00	34.00	62.69	109	115
115	28ABD	15.00	860.00	27.00	45.00	58.50	81.62	109	115
116	29	12.10	860.00	0	15.00	169.00	537.94	116	116
117	30	4.10	430.00	0	10.00	13.00	74.62	117	117
118	31A	26.10	950.00	0	20.00	10.00	21.51	118	120
119	31B	26.10	950.00	0	20.00	17.00	36.57	118	120

120	31AB	26.10	950.00	0	40.00	27.00	38.71	118	120
121	32	9.00	120.00	0	10.00	24.00	132.93	121	121
122	33	1.20	28.00	1.30	5.00	122.00	1758.97	122	123
123	34	1.50	1600.00	0	5.00	62.00	327.24	122	123
124	35	15.00	410.00	0	5.00	33.50	184.78	124	124
125	36A	1.80	82.00	0	5.00	78.50	1040.81	125	125
126	36C	1.00	70.00	.10	0	102.00	8792.69	126	126
127	37	31.00	325.00	0	5.00	218.50	801.00	127	127
128	38	2.00	60.00	0	10.00	75.50	567.21	128	128
129	39	.50	17.00	.02	10.00	153.00	1267.97	129	129
130	40	.30	1.00	0	0	135.00	70553.36	130	130
131	41	40.00	575.00	0	12.00	29.00	67.70	131	132
132	42	10.80	330.00	0	12.00	25.50	110.46	131	132
133	43	27.00	1800.00	0	15.00	220.50	462.11	133	133
134	44A	.70	18.00	0	10.00	7.00	57.41	134	136
135	44B	.70	18.00	0	12.00	5.50	37.88	134	136
136	44AB	.70	18.00	0	22.00	12.50	47.81	134	136
137	45A	6.80	230.00	0	5.00	14.50	123.57	137	141
138	45B	6.80	230.00	0	20.00	10.50	35.99	137	141
139	45C	9.00	250.00	0	12.00	24.50	114.63	137	141
140	45Y	6.80	230.00	0	20.00	25.00	85.69	137	141
141	45Z	9.00	250.00	0	32.00	35.00	78.42	137	141
142	46	14.00	380.00	0	15.00	5.00	17.29	142	142
143	47A	15.00	400.00	0	15.00	5.00	16.85	143	146
144	47B	17.00	430.00	0	45.00	2.00	3.03	143	146
145	47Y	15.00	400.00	0	30.00	10.00	21.22	143	146
146	47Z	17.00	430.00	0	60.00	7.00	8.39	143	146
147	47C	15.00	400.00	0	15.00	5.00	16.85	147	147
148	49	10.00	300.00	0	15.00	5.00	19.34	148	148
149	50A	20.50	610.00	0	20.00	3.50	8.65	149	150
150	50B	22.70	630.00	0	20.00	3.50	8.34	149	150
151	51	42.00	950.00	0	75.00	.50	.42	151	151
152	52	0	0	0	2.00	151.50	6514.50	152	153
153	53	2.00	70.00	0	3.00	155.00	2953.81	152	153
154	54	.50	70.00	0	1.00	126.50	6314.50	154	154
155	56	7.00	450.00	0	5.00	25.50	188.39	155	155
156	57	5.00	430.00	0	5.00	17.00	139.82	156	156
157	58	37.00	1600.00	0	12.00	66.50	136.20	157	160
158	55	33.00	1900.00	0	10.00	22.50	48.55	157	160
159	59	48.00	2100.00	0	20.00	45.50	66.25	157	160
160	60	15.00	200.00	0	10.00	23.00	102.95	157	160
161	61A	32.00	650.00	0	60.00	6.50	6.89	161	163
162	61B	32.00	650.00	0	60.00	25.00	26.50	161	163
163	61AB	32.00	650.00	0	120.00	31.50	19.20	161	163
164	62	37.00	1100.00	0	60.00	16.50	16.37	164	164
165	63	.50	4.00	.02	2.00	128.50	4823.03	165	165
166	64	.50	4.00	0	2.00	71.00	2666.87	166	166
167	65	.20	2.00	0	12.00	58.00	411.60	167	167
168	66	.40	4.00	0	15.00	89.00	502.33	168	168
169	67	.40	4.00	1.00	5.00	31.00	498.17	169	169
170	68	32.80	430.00	0	40.00	36.50	52.23	170	170
171	69	5.00	1700.00	0	15.00	25.00	74.67	171	171
172	70	.70	12.00	0	15.00	22.00	122.48	172	172
173	72	34.50	450.00	0	40.00	27.50	38.69	173	173
174	73	8.00	150.00	0	15.00	96.00	408.76	174	174
175	74	9.60	750.00	0	15.00	10.00	34.43	175	175
176	75A	5.40	98.00	3.00	3.00	81.00	1019.73	176	178
177	75B	5.40	98.00	3.00	3.00	71.50	900.13	176	178
178	75AB	5.40	98.00	3.00	6.00	152.50	1334.02	176	178
179	76	4.50	150.00	10.00	0	117.00	2235.37	179	179
180	79	15.00	3300.00	0	18.00	71.50	129.28	180	180
181	80	34.00	440.00	0	10.00	35.00	97.75	181	181
182	81A	2.00	9.00	0	2.00	141.00	3896.08	182	184
183	81B	2.00	9.00	0	2.00	138.00	3813.18	182	184
184	81AB	2.00	9.00	0	4.00	279.00	4693.33	182	184
185	82	32.00	420.00	0	25.00	9.50	18.31	185	185

186	83	6.00	40.00	0	15.00	30.50	142.38	186	186
187	84	43.00	1120.00	0	60.00	30.50	29.15	187	187
188	85A	28.00	1000.00	0	20.00	45.50	94.72	188	190
189	85B	28.00	1000.00	0	20.00	66.50	138.44	188	190
190	85AB	28.00	1000.00	0	40.00	112.00	157.10	188	190
191	86	2.50	20.00	0	2.00	63.50	1583.87	191	191
192	87	4.00	200.00	0	30.00	31.50	81.06	192	192
193	88A	5.30	90.00	0	2.00	79.50	1270.34	193	195
194	88B	5.30	90.00	0	5.00	47.50	487.35	193	195
195	88AB	5.30	90.00	0	7.00	127.00	1052.01	193	195
196	89	0	0	0	5.00	35.00	602.00	196	196
197	90	2.00	85.00	0	2.00	61.50	1464.57	197	197
198	91	5.90	92.00	0	15.00	35.50	163.16	198	198
199	92A	43.30	610.00	0	45.00	40.00	47.91	199	201
200	92B	43.30	610.00	0	45.00	40.00	47.91	199	201
201	92AB	43.30	610.00	0	90.00	80.00	58.90	199	201
202	93	0	0	0	3.00	43.00	1232.67	202	202
203	94	0	0	0	3.00	48.00	1376.00	203	203
204	95	2.50	25.00	0	35.00	79.00	186.24	204	205
205	96	0	0	0	3.00	41.00	1175.33	204	205
206	97	1.00	35.00	0	10.00	91.00	727.57	206	207
207	98	0	0	0	3.00	74.50	2135.67	206	207
208	99	0	0	0	1.00	29.00	2494.00	208	209
209	100	.50	1.00	0	2.00	95.50	3618.25	208	209
210	101	0	0	0	2.00	101.50	4364.50	210	210
211	102	0	0	0	3.00	59.50	1705.67	211	211
212	103	0	0	0	3.00	57.50	1648.33	212	212
213	104	0	0	0	10.00	37.50	322.50	213	213
214	105	0	0	0	16.00	31.50	169.31	214	214
215	106	0	0	0	8.00	18.50	198.88	215	215
216	107	0	0	0	5.00	14.00	240.80	216	216

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

RANK	INST	S(I)	NORMS	TIME	WGT	VOL	POW
1	130	135.00	70553.36	0	.3	1	0
2	126	102.00	8792.69	0	1.0	70	0
3	152	151.50	6514.50	2.0	0	0	0
4	154	126.50	6314.50	1.0	.5	70	0
5	165	128.50	4823.03	2.0	.5	4	0
6	184	279.00	4693.33	4.0	2.0	9	0
7	210	101.50	4364.50	2.0	0	0	0
8	182	141.00	3896.08	2.0	2.0	9	0
9	183	138.00	3813.18	2.0	2.0	9	0
10	209	95.50	3618.25	2.0	.5	1	0
11	153	155.00	2953.81	3.0	2.0	70	0
12	166	71.00	2666.87	2.0	.5	4	0
13	208	29.00	2494.00	1.0	0	0	0
14	179	117.00	2235.37	0	4.5	150	10
15	207	74.50	2135.67	3.0	0	0	0
16	89	185.50	1831.36	5.0	5.8	100	0
17	122	122.00	1758.97	5.0	1.2	28	1
18	211	59.50	1705.67	3.0	0	0	0
19	80	38.50	1655.50	2.0	0	0	0
20	212	57.50	1648.33	3.0	0	0	0
21	191	63.50	1583.87	2.0	2.5	20	0
22	197	61.50	1464.57	2.0	2.0	85	0
23	4	90.00	1452.44	5.0	.5	10	0
24	85	274.50	1392.71	0	9.0	550	75
25	203	48.00	1376.00	3.0	0	0	0
26	178	152.50	1334.02	6.0	5.4	98	3
27	5	143.50	1322.87	9.0	.5	10	0
28	193	79.50	1270.34	2.0	5.3	90	0
29	129	153.00	1267.97	10.0	.5	17	0
30	202	43.00	1232.67	3.0	0	0	0
31	205	41.00	1175.33	3.0	0	0	0
32	3	53.50	1062.84	4.0	.5	10	0
33	195	127.00	1052.01	7.0	5.3	90	0
34	125	78.50	1040.81	5.0	1.8	82	0
35	176	81.00	1019.73	3.0	5.4	98	3
36	87	125.50	1012.67	10.0	1.0	20	0
37	177	71.50	900.13	3.0	5.4	98	3
38	127	218.50	801.00	5.0	31.0	325	0
39	206	91.00	727.57	10.0	1.0	35	0
40	196	35.00	602.00	5.0	0	0	0
41	128	75.50	567.21	10.0	2.0	60	0
42	116	169.00	537.94	15.0	12.1	860	0
43	6	171.50	525.45	10.0	11.0	560	75
44	168	89.00	502.33	15.0	.4	4	0
45	169	31.00	498.17	5.0	.4	4	1
46	1	54.50	496.43	8.0	2.6	11	0
47	194	47.50	487.35	5.0	5.3	90	0
48	82	32.00	480.75	4.0	3.0	22	0
49	133	220.50	462.11	15.0	27.0	1800	0
50	167	58.00	411.60	12.0	.2	2	0
51	174	96.00	408.76	15.0	8.0	150	0
52	71	30.00	407.64	6.0	.6	2	0
53	72	64.50	387.11	14.0	.6	2	0
54	73	37.00	382.03	8.0	.6	2	0
55	70	34.50	356.22	8.0	.6	2	0
56	123	62.00	327.24	5.0	1.5	1600	0

57	76	62.00	326.53	16.0	.6	2	0
58	213	37.50	322.50	10.0	0	0	0
59	86	110.50	296.56	10.0	17.3	660	75
60	84	43.50	272.58	12.0	3.0	22	0
61	74	25.00	258.13	8.0	.6	2	0
62	79	76.50	249.88	26.0	.6	2	0
63	77	51.50	241.64	18.0	.6	2	0
64	216	14.00	240.80	5.0	0	0	0
65	46	135.50	207.30	50.0	10.3	120	0
66	62	159.50	207.17	60.0	10.3	120	0
67	44	134.50	205.77	50.0	10.3	120	0
68	23	110.50	205.64	40.0	10.3	120	0
69	47	96.50	201.37	35.0	10.3	120	0
70	85	96.50	200.53	20.0	16.3	640	75
71	27	72.50	199.76	25.0	10.3	120	0
72	215	18.50	198.88	8.0	0	0	0
73	25	71.50	197.01	25.0	10.3	120	0
74	11	47.50	192.58	15.0	10.3	120	0
75	155	25.50	188.39	5.0	7.0	450	0
76	45	112.00	188.08	45.0	10.3	120	0
77	204	79.00	186.24	35.0	2.5	25	0
78	78	39.50	185.33	18.0	.6	2	0
79	124	33.50	184.78	5.0	15.0	410	0
80	24	88.00	183.64	35.0	10.3	120	0
81	22	87.00	181.55	35.0	10.3	120	0
82	9	63.00	173.59	25.0	10.3	120	0
83	214	31.50	169.31	16.0	0	0	0
84	68	186.50	166.70	90.0	10.3	120	0
85	67	186.50	166.70	90.0	10.3	120	0
86	198	35.50	163.16	15.0	5.9	92	0
87	60	162.50	162.10	80.0	10.3	120	0
88	56	162.50	162.10	80.0	10.3	120	0
89	58	161.50	161.10	80.0	10.3	120	0
90	54	161.50	161.10	80.0	10.3	120	0
91	26	49.00	160.77	20.0	10.3	120	0
92	190	112.00	157.10	40.0	28.0	1000	0
93	39	137.50	155.16	70.0	10.3	120	0
94	33	137.50	155.16	70.0	10.3	120	0
95	61	123.50	149.15	65.0	10.3	120	0
96	57	123.50	149.15	65.0	10.3	120	0
97	59	139.00	147.19	75.0	10.3	120	0
98	55	139.00	147.19	75.0	10.3	120	0
99	69	213.50	145.48	120.0	10.3	120	0
100	186	30.50	142.38	15.0	6.0	40	0
101	65	189.50	140.23	110.0	10.3	120	0
102	156	17.00	139.82	5.0	5.0	430	0
103	43	99.50	139.79	55.0	10.3	120	0
104	37	99.50	139.79	55.0	10.3	120	0
105	63	188.50	139.49	110.0	10.3	120	0
106	40	115.00	138.88	65.0	10.3	120	0
107	34	115.00	138.88	65.0	10.3	120	0
108	189	66.50	138.44	20.0	28.0	1000	0
109	41	98.50	138.39	55.0	10.3	120	0
110	35	98.50	138.39	55.0	10.3	120	0
111	38	114.00	137.67	65.0	10.3	120	0
112	32	114.00	137.67	65.0	10.3	120	0
113	157	66.50	136.20	12.0	37.0	1600	0
114	49	164.50	133.20	100.0	10.3	120	0
115	121	24.00	132.93	10.0	9.0	120	0
116	12	25.00	132.62	10.0	10.3	120	0
117	180	71.50	129.28	18.0	15.0	3300	0
118	64	166.00	128.37	105.0	10.3	120	0
119	66	150.50	127.88	95.0	10.3	120	0
120	10	24.00	127.31	10.0	10.3	120	0
121	18	90.00	126.45	55.0	10.3	120	0
122	14	90.00	126.45	55.0	10.3	120	0

123	20	74.50	125.11	45.0	10.3	120	0
124	16	74.50	125.11	45.0	10.3	120	0
125	103	41.00	125.03	15.0	13.2	690	15
126	137	14.50	123.57	5.0	6.8	230	0
127	172	22.00	122.48	15.0	.7	12	0
128	75	14.50	120.73	10.0	.6	2	0
129	50	142.00	120.66	95.0	10.3	120	0
130	48	141.00	119.81	95.0	10.3	120	0
131	107	60.00	119.44	30.0	13.2	690	15
132	53	126.50	119.27	85.0	10.3	120	0
133	51	125.50	118.33	85.0	10.3	120	0
134	92	23.00	117.12	15.0	2.0	40	5
135	42	76.00	116.27	50.0	10.3	120	0
136	36	76.00	116.27	50.0	10.3	120	0
137	139	24.50	114.63	12.0	9.0	250	0
138	132	25.50	110.46	12.0	10.8	330	0
139	28	117.00	110.31	85.0	10.3	120	0
140	30	101.50	107.48	75.0	10.3	120	0
141	160	23.00	102.95	10.0	15.0	200	0
142	52	103.00	102.75	80.0	10.3	120	0
143	83	11.50	101.70	8.0	3.0	22	0
144	181	35.00	97.75	10.0	34.0	440	0
145	21	52.00	96.77	40.0	10.3	120	0
146	17	52.00	96.77	40.0	10.3	120	0
147	2	12.50	95.00	10.0	2.0	40	0
148	112	51.50	94.96	30.0	15.0	860	27
149	19	51.00	94.91	40.0	10.3	120	0
150	15	51.00	94.91	40.0	10.3	120	0
151	188	45.50	94.72	20.0	28.0	1000	0
152	108	62.50	92.35	45.0	13.2	690	15
153	81	27.00	90.42	12.0	17.0	720	0
154	31	79.00	89.15	70.0	10.3	120	0
155	29	78.00	88.02	70.0	10.3	120	0
156	105	43.50	86.59	30.0	13.2	690	15
157	140	25.00	85.69	20.0	6.8	230	0
158	93	30.50	82.25	30.0	2.0	40	5
159	115	58.50	81.62	45.0	15.0	860	27
160	192	31.50	81.06	30.0	4.0	200	0
161	141	35.00	78.42	32.0	9.0	250	0
162	99	35.00	77.06	15.0	24.0	1740	0
163	171	25.00	74.67	15.0	5.0	1700	0
164	117	13.00	74.62	10.0	4.1	430	0
165	110	27.00	73.38	15.0	15.0	860	27
166	13	54.00	70.14	60.0	10.3	120	0
167	131	29.00	67.70	12.0	40.0	575	0
168	109	24.50	66.59	15.0	15.0	860	27
169	159	45.50	66.25	20.0	48.0	2100	0
170	90	29.50	65.01	15.0	17.6	1200	60
171	8	27.00	64.12	30.0	10.3	120	0
172	7	27.00	64.12	30.0	10.3	120	0
173	114	34.00	62.69	30.0	15.0	860	27
174	201	80.00	58.90	90.0	43.3	610	0
175	113	31.50	58.08	30.0	15.0	860	27
176	104	19.00	57.94	15.0	13.2	690	15
177	134	7.00	57.41	10.0	.7	18	0
178	95	25.00	57.17	15.0	33.0	360	25
179	170	36.50	52.23	40.0	32.8	430	0
180	158	22.50	48.55	10.0	33.0	1900	0
181	200	40.00	47.91	45.0	43.3	610	0
182	199	40.00	47.91	45.0	43.3	610	0
183	136	12.50	47.81	22.0	.7	18	0
184	106	21.50	42.80	30.0	13.2	690	15
185	120	27.00	38.71	40.0	26.1	950	0
186	173	27.50	38.69	40.0	34.5	450	0
187	91	7.50	38.19	15.0	2.0	40	5
188	135	5.50	37.88	12.0	.7	18	0

189	119	17.00	36.57	20.0	26.1	950	0
190	101	17.50	36.12	20.0	30.3	870	0
191	138	10.50	35.99	20.0	6.8	230	0
192	175	10.00	34.43	15.0	9.6	750	0
193	94	16.00	31.38	10.0	10.0	860	200
194	100	7.50	30.12	15.0	5.2	560	0
195	187	30.50	29.15	60.0	43.0	1120	0
196	162	25.00	26.50	60.0	32.0	650	0
197	98	14.50	26.01	30.0	12.0	1700	4
198	118	10.00	21.51	20.0	26.1	950	0
199	145	10.00	21.22	30.0	15.0	400	0
200	96	7.50	19.58	15.0	12.0	1700	4
201	148	5.00	19.34	15.0	10.0	300	0
202	163	31.50	19.20	120.0	32.0	650	0
203	111	7.00	19.03	15.0	15.0	860	27
204	185	9.50	18.31	25.0	32.0	420	0
205	97	7.00	18.28	15.0	12.0	1700	4
206	142	5.00	17.29	15.0	14.0	380	0
207	147	5.00	16.85	15.0	15.0	400	0
208	143	5.00	16.85	15.0	15.0	400	0
209	164	16.50	16.37	60.0	37.0	1100	0
210	149	3.50	8.65	20.0	20.5	610	0
211	146	7.00	8.39	60.0	17.0	430	0
212	150	3.50	8.34	20.0	22.7	630	0
213	102	2.50	7.62	15.0	13.2	690	15
214	161	6.50	6.89	60.0	32.0	650	0
215	144	2.00	3.03	45.0	17.0	430	0
216	151	.50	.42	75.0	42.0	950	0

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

FIRST COMBINATION

3180.50 77.80 1736 89.4 86.0 18.9 29
130 126 152 154 165 184 210 209 166 179 207 89 122 211 80 212 191 197 4 88
203 178 193 129 202 205 125 127 82

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

OF THE 668303 COMBINATIONS CONSIDERED 3970 FELL WITHIN THE CONSTRAINTS.
THE FOLLOWING 20 HAVE THE HIGHEST TOTAL S

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3202.00	74.80	1714	89.4	86.0	18.0	28	303

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
5	VO MAPS (3AB)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1,5,1,5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3180.50	77.80	1736	89.4	86.0	18.9	29	1

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
82	GYRO INCL(A3 TO SAMP SITE + SIP)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3153.00	78.30	1739	89.4	86.0	19.1	29	16

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
82	GYRO INCL(A3 TO SAMP SITE + SIP)
87	VO MAPS INCL (SLOPE)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1,5,1,5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3152.00	76.80	1784	89.4	83.0	18.1	28	434

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
153	CHARGED DUST DET(ELECTROSTATICS)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3147.00	74.80	1714	89.4	86.0	18.9	29	304

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
3	VO MAPS (X SECT TOPO)
196	SAMPLING PACK.(SOIL DENSITY)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3145.50	89.80	2124	89.4	86.0	20.3	29	308

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
3	VO MAPS (X SECT TOPO)
124	SOLAR PLAS SPEC (35AB)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3145.00	74.80	1714	89.4	85.0	18.6	28	335

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
196	SAMPLING PACK.(SOIL DENSITY)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3144.00	77.80	1736	89.4	85.0	19.2	29	33

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
82	GYRO INCL(A3 TO SAMP SITE + SIP)
3	VO MAPS (X SECT TOPO)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3143.50	89.80	2124	89.4	85.0	20.0	28	340

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
124	SOLAR PLAS SPEC (35AB)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3143.50	77.00	1674	89.4	85.0	18.1	27	470

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
127	PARTICLE SPEC(37AB)
82	GYRO INCL(A3 TO SAMP SITE + SIP)
87	VO MAPS INCL (SLOPE)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1,5,1,5,,5,,5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3143.00	75.20	1718	90.4	86.0	19.1	29	305

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
3	VO MAPS (X SECT TOPO)
169	THERM PROBE(LAND GEAR THER COND)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3142.50	74.80	1714	89.4	84.0	18.2	28	248

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
196	SAMPLING PACK.(SOIL DENSITY)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3141.00	89.80	2124	89.4	84.0	19.6	28	253

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
124	SOLAR PLAS SPEC (35AB)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1,5,1,5,,5',5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3141.00	75.20	1718	90.4	85.0	18.8	28	336

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
169	THERM PROBE(LAND GEAR THER COND)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1,5,1,5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3140.50	74.80	1714	89.4	84.0	18.2	28	256

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
196	SAMPLING PACK.(SOIL DENSITY)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3140.00	75.40	1716	89.4	86.0	19.0	28	337

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
71	VO HL ST(ORE MINER KIND + AMT)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1,5,1,5,,5,,5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3139.00	89.80	2124	89.4	84.0	19.6	28	261

130 PERS INTEG DOSIMET(CUM RAD DOSE)
126 SURVEY RATE METER(36CD)
152 VO(ELECTROSTATICS)

165 PLAT RESIST BRIDGE(LAND GEAR T)
184 JS(81AB)
210 VO (EROSION)
209 INCL(ANGLE OF REPOSE)
166 THERMO COUPLE (BOOT TEMP)
179 LEM TV TRACKER(76ABC)
207 VO(TRANSPORTATION)
89 VO MAPS HC(OCCURENCE STEEP SLOPE
122 SAMP CULT PH RO(DET LIFE FORMS)
211 VO (RADIATION DAMAGE)
80 VO SP (ABRASIVE HARDNESS)
212 VO (MICROMETEORITE ACCRETION)
191 JS/PENETROMETER(PENETRAT RESIST)
197 TETHER SPHERE(PENETRAT RESIST)
4 VO MAPS (DEPOSITION)
88 DESCENT CAMERA (17ABCD)
203 VO (SINTERING)
178 HC LEM TARGET(75AB)
193 HC SP-LENS(BEARING STRENGTH)
129 CHEM REACTIVITY DET(CHEM REACT)
205 VO (VAC. OUTGAS.)
125 SURVEY RATE METER(36AB)
127 PARTICLE SPEC(37AB)
124 SOLAR PLAS SPEC (35AB)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3138.50	75.20	1718	90.4	84.0	18.4	28	249

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
4	VO MAPS (DEPOSITION)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
169	THERM PROBE(LAND GEAR THER COND)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1   6,1.5,1.5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3137.50	75.40	1716	89.4	85.0	18.6	28	250

130 PERS INTEG DOSIMET(CUM RAD DOSE)
126 SURVEY RATE METER(36CD)
152 VO(ELECTROSTATICS)

165 PLAT RESIST BRIDGE(LAND GEAR T)
184 JS(81AB)
210 VO (EROSION)
209 INCL(ANGLE OF REPOSE)
166 THERMO COUPLE (BOOT TEMP)
179 LEM TV TRACKER(76ABC)
207 VO(TRANSPORTATION)
89 VO MAPS HC(OCCURENCE STEEP SLOPE
122 SAMP CULT PH RO(DET LIFE FORMS)
211 VO (RADIATION DAMAGE)
80 VO SP (ABRASIVE HARDNESS)
212 VO (MICROMETEORITE ACCRETION)
191 JS/PENETROMETER(PENETRAT RESIST)
197 TETHER SPHERE(PENETRAT RESIST)
4 VO MAPS (DEPOSITION)
88 DESCENT CAMERA (17ABCD)
203 VO (SINTERING)
178 HC LEM TARGET(75AB)
193 HC SP-LENS(BEARING STRENGTH)
129 CHEM REACTIVITY DET(CHEM REACT)
202 VO (EFFECTS THERMAL CYCLING)
125 SURVEY RATE METER(36AB)
127 PARTICLE SPEC(37AB)
71 VO HL ST(ORE MINER KIND + AMT)

APOLLO INSTRUMENTATION MATRIX ANALYSIS 1ST FLIGHT ALT. 1 6,1,5,1,5,.5,.5

TOTAL S	WGT	VOL	POW	TIME	AVG	NOI	COMB
3137.50	81.80	2164	89.4	86.0	20.1	29	307

130	PERS INTEG DOSIMET(CUM RAD DOSE)
126	SURVEY RATE METER(36CD)
152	VO(ELECTROSTATICS)
165	PLAT RESIST BRIDGE(LAND GEAR T)
184	JS(81AB)
210	VO (EROSION)
209	INCL(ANGLE OF REPOSE)
166	THERMO COUPLE (BOOT TEMP)
179	LEM TV TRACKER(76ABC)
207	VO(TRANSPORTATION)
89	VO MAPS HC(OCCURENCE STEEP SLOPE
122	SAMP CULT PH RO(DET LIFE FORMS)
211	VO (RADIATION DAMAGE)
80	VO SP (ABRASIVE HARDNESS)
212	VO (MICROMETEORITE ACCRETION)
191	JS/PENETROMETER(PENETRAT RESIST)
197	TETHER SPHERE(PENETRAT RESIST)
88	DESCENT CAMERA (17ABCD)
203	VO (SINTERING)
178	HC LEM TARGET(75AB)
193	HC SP-LENS(BEARING STRENGTH)
129	CHEM REACTIVITY DET(CHEM REACT)
202	VO (EFFECTS THERMAL CYCLING)
205	VO (VAC. OUTGAS.)
125	SURVEY RATE METER(36AB)
127	PARTICLE SPEC(37AB)
3	VO MAPS (X SECT TOPO)
155	GM (GRAVITY)

THE FOLLOWING 80 HAVE THE NEXT HIGHEST TOTAL S

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    3137.00      76.00        1654      89.4      86.0     19.1    29       9
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 196
    3136.50      75.20        1718      90.4      84.0     18.4    28     257
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127 169
    3135.50      91.00        2064      89.4      86.0     20.4    29      13
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 124
    3135.50      75.40        1716      89.4      85.0     18.6    28     258
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127  71
    3135.50      74.80        1714      89.4      84.0     18.4    28     295
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127 196
    3135.50      81.80        2164      89.4      85.0     19.9    28     339
130 126 152 154 165 184 210 209 166 179 207  89 122 211 212 191 197   4  88 203
178 193 129 202 205 125 127 155
    3134.00      89.80        2124      89.4      84.0     19.8    28     300
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127 124
    3133.00      76.40        1658      90.4      86.0     19.3    29      10
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 169
    3133.00      81.80        2164      89.4      84.0     19.4    28     252
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 125 127 155
    3131.50      77.80        1736      89.4      85.0     18.8    28      93
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 125 127  82 196
    3131.50      75.20        1718      90.4      84.0     18.6    28     296
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127 169
    3131.00      81.80        2164      89.4      84.0     19.5    28     260
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127 155
    3130.50      75.40        1716      89.4      85.0     18.8    28     297
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127  71
    3130.00      92.80        2146      89.4      85.0     20.2    28      98
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 125 127  82 124
    3129.00      79.80        2144      89.4      86.0     21.1    29     309
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127   3 156
    3127.50      78.20        1740      90.4      85.0     19.0    28      94
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 125 127  82 169
    3127.50      83.00        2104      89.4      86.0     20.3    29      12
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 155
    3127.00      79.80        2144      89.4      85.0     20.8    28     341
130 126 152 154 165 184 210 209 166 179 207  89 122 211 212 191 197   4  88 203
178 193 129 202 205 125 127 156
    3126.50      78.40        1738      89.4      86.0     19.3    28      95
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
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203 178 193 129 125 127  82  71
   3126.50       81.60         1944        89.4        86.0       21.9      29       310
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127   3 137
   3126.00       81.80         2164        89.4        84.0       19.6      28       299
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127 155
   3126.00       74.80         1714        89.4        86.0       19.8      29       306
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127   3 216
   3126.00       74.80         1714        89.4        84.0       18.6      28       327
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 191 197   4  88 203
178 193 129 202 205 125 127 196
   3125.50       77.30         1726        89.4        86.0       19.5      29        34
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127  82 196
   3124.50       75.60         1643        89.4        85.0       18.3      28       236
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127   1
   3124.50       79.80         2144        89.4        84.0       20.4      28       294
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 125 127 156
   3124.50       89.80         2124        89.4        84.0       20.0      28       332
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 191 197   4  88 203
178 193 129 202 205 125 127 124
   3124.50       81.60         1944        89.4        85.0       21.7      28       342
130 126 152 154 165 184 210 209 166 179 207  89 122 211 212 191 197   4  88 203
178 193 129 202 205 125 127 137
   3124.00       92.30         2136        89.4        86.0       20.8      29        38
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127  82 124
   3124.00       74.80         1714        89.4        85.0       19.5      28       338
130 126 152 154 165 184 210 209 166 179 207  89 122 211 212 191 197   4  88 203
178 193 129 202 205 125 127 216
   3124.00       74.80         1714        89.4        84.0       18.6      28       343
130 126 152 154 165 184 210 209 166 179 207  89 122  80 212 191 197   4  88 203
178 193 129 202 205 125 127 196
   3122.50       79.80         2144        89.4        84.0       20.4      28       262
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127 156
   3122.50       89.80         2124        89.4        84.0       20.0      28       348
130 126 152 154 165 184 210 209 166 179 207  89 122  80 212 191 197   4  88 203
178 193 129 202 205 125 127 124
   3122.00       84.80         2186        89.4        85.0       20.1      28        97
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 125 127  82 155
   3122.00       81.60         1944        89.4        84.0       21.3      28       295
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 125 127 137
   3122.00       72.80         1629        89.4        85.0       18.5      28       311
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191   4  88 203
178 193 129 202 205 125 127 196
   3122.00       75.20         1718        90.4        84.0       18.8      28       328
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 191 197   4  88 203
178 193 129 202 205 125 127 169
   3121.50       77.70         1730        90.4        86.0       19.7      29        35
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127  82 169
   3121.50       74.80         1714        89.4        84.0       19.0      28       251
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 125 127 216
   3121.00       75.30         1717        89.4        82.0       18.1      28       264
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 202 205 125 127  87
   3121.00       75.40         1716        89.4        85.0       19.0      28       329
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 191 197   4  88 203
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178 193 129 202 205 125 127  71
   3120.50      78.10         3308      88.1       86.0      20.2      29       43
130 126 152 154 165 184 210 209 166 179 207  89 211  80 212 191 197   4  88 203
178 193 129 202 205 125 127  82 123
   3120.50      87.80         2039      89.4       85.0      19.9      28       316
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191   4  88 203
178 193 129 202 205 125 127 124
   3120.00      81.60         1944      89.4       84.0      21.3      28       283
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127 137
   3120.00      72.30         1694      89.4       85.0      18.5      28       319
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 197   4  88 203
178 193 129 202 205 125 127 196
   3120.00      75.20         1718      90.4       84.0      18.8      28       344
130 126 152 154 165 184 210 209 166 179 207  89 122  80 212 191 197   4  88 203
178 193 129 202 205 125 127 169
   3119.50      77.80         1736      89.4       86.0      19.6      28       162
130 126 152 154 165 184 210 209 166 179 207  89 122 211 191 197   4  88 203 178
193 129 202 205 125 127  82 196
   3119.50      74.80         1714      89.4       84.0      19.1      28       259
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 205 125 127 216
   3119.00      81.00         2084      89.4       86.0      21.2      29        14
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 156
   3119.00      75.40         1716      89.4       85.0      19.1      28       345
130 126 152 154 165 184 210 209 166 179 207  89 122  80 212 191 197   4  88 203
178 193 129 202 205 125 127  71
   3118.50      87.30         2104      89.4       85.0      19.9      28       324
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 197   4  88 203
178 193 129 202 205 125 127 124
   3118.00      92.80         2146      89.4       86.0      21.0      28       166
130 126 152 154 165 184 210 209 166 179 207  89 122 211 191 197   4  88 203 178
193 129 202 205 125 127  82 124
   3118.00      73.20         1633      90.4       85.0      18.7      28       312
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191   4  88 203
178 193 129 202 205 125 127 169
   3117.50      77.80         1736      89.4       86.0      19.7      28       169
130 126 152 154 165 184 210 209 166 179 207  89 122 212 191 197   4  88 203 178
193 129 202 205 125 127  82 196
   3117.50      79.80         2144      89.4       84.0      20.6      28       301
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
178 193 129 202 205 125 127 156
   3117.00      73.40         1631      89.4       86.0      18.9      28       313
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191   4  88 203
178 193 129 202 205 125 127  71
   3117.00      74.30         1713      89.4       86.0      18.7      29       396
130 126 152 154 165 184 210 166 179 207  89 122 211  80 212 191 197   4  88 203
178 193 129 202 205 125 127 208 196
   3116.50      82.80         1884      89.4       86.0      22.1      29        15
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 193 129 202 205 127  82 137
   3116.50      74.80         1714      89.4       85.0      18.5      28       280
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 129 202 205 125 127 194
   3116.50      81.80         2164      89.4       84.0      19.8      28       331
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 191 197   4  88 203
178 193 129 202 205 125 127 155
   3116.50      78.30         1739      89.4       85.0      18.5      27       958
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
203 178 125 127  82 195  87
   3116.00      84.30         2176      89.4       86.0      20.7      29        37
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197  88 203
178 193 129 202 205 125 127  82 155
   3116.00      76.00         1654      89.4       86.0      19.9      29        11
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197   4  88
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203 178 193 129 202 205 127  82 216
   3116.00      92.80         2146        89.4        86.0       21.1       28        173
130 126 152 154 165 184 210 209 166 179 207  89 122 212 191 197    4  88 203 178
193 129 202 205 125 127  82 124
   3116.00      72.70         1698        90.4        85.0       18.7       28        320
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 197    4  88 203
178 193 129 202 205 125 127 169
   3115.50      78.60         1665        89.4        86.0       18.9       28         82
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
203 178 193 129 202 127  82   1
   3115.50      78.20         1740        90.4        86.0       19.8       28        163
130 126 152 154 165 184 210 209 166 179 207  89 122 211 191 197    4  88 203 178
193 129 202 205 125 127  82 169
   3115.50      89.30         2123        89.4        86.0       20.1       29        400
130 126 152 154 165 184 210 166 179 207  89 122 211  80 212 191 197    4  88 203
178 193 129 202 205 125 127 208 124
   3115.00      81.60         1944        89.4        84.0       21.5       28        302
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
178 193 129 202 205 125 127 137
   3115.00      72.90         1696        89.4        86.0       19.0       28        321
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 197    4  88 203
178 193 129 202 205 125 127  71
   3114.50      74.80         1714        89.4        84.0       19.3       28        298
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
178 193 129 202 205 125 127 216
   3114.50      81.80         2164        89.4        84.0       19.9       28        347
130 126 152 154 165 184 210 209 166 179 207  89 122  80 212 191 197    4  88 203
178 193 129 202 205 125 127 155
   3114.00      77.30         1735        89.4        85.0       19.0       29         56
130 126 152 154 165 184 210 166 179 207  89 122 211  80 212 191 197    4  88 203
178 193 129 202 205 125 127  82 208
   3113.50      82.80         2166        89.4        85.0       21.0       28         99
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
203 178 193 129 125 127  82 156
   3113.50      78.20         1740        90.4        86.0       19.9       28        170
130 126 152 154 165 184 210 209 166 179 207  89 122 212 191 197    4  88 203 178
193 129 202 205 125 127  82 169
   3113.00      74.70         1717        90.4        86.0       18.9       29        397
130 126 152 154 165 184 210 166 179 207  89 122 211  80 212 191 197    4  88 203
178 193 129 202 205 125 127 208 169
   3112.50      79.80         2079        89.4        85.0       19.8       28        315
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191    4  88 203
178 193 129 202 205 125 127 155
   3112.50      74.30         1710        89.4        85.0       18.9       28        388
130 126 152 154 165 184 210 209 179 207  89 122 211  80 212 191 197    4  88 203
178 193 129 202 205 125 127 196
   3112.00      74.80         1714        89.4        84.0       18.9       29        287
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
203 193 129 202 205 125 127 176 196
   3111.00      84.60         1966        89.4        85.0       21.9       28        100
130 126 152 154 165 184 210 209 166 179 207  89 122 211  80 212 191 197    4  88
203 178 193 129 125 127  82 137
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TIMES INCLUDED	INSTRUMENT	INSTRUMENTS(MEASUREMENTS)
100	130	PERS INTEG DOSIMET(CUM RAD DOSE)
100	126	SURVEY RATE METER(36CD)
99	152	VO(ELECTROSTATICS)
100	165	PLAT RESIST BRIDGE(LAND GEAR T)
100	184	JS(81AB)
100	210	VO (EROSION)
96	209	INCL(ANGLE OF REPOSE)
1	153	CHARGED DUST DET(ELECTROSTATICS)
99	166	THERMO COUPLE (BOOT TEMP)
4	208	VO(ANGLE OF REPOSE)
100	179	LEM TV TRACKER(76ABC)
100	207	VO(TRANSPORTATION)
100	89	VO MAPS HC(OCCURENCE STEEP SLOPE
99	122	SAMP CULT PH RO(DET LIFE FORMS)
92	211	VO (RADIATION DAMAGE)
86	80	VO SP (ABRASIVE HARDNESS)
92	212	VO (MICROMETEORITE ACCRETION)
96	191	JS/PENETROMETER(PENETRAT RESIST)
95	197	TETHER SPHERE(PENETRAT RESIST)
87	4	VO MAPS (DEPOSITION)
100	88	DESCENT CAMERA (17ABCD)
92	203	VO (SINTERING)
99	178	HC LEM TARGET(75AB)
1	5	VO MAPS (3AB)
98	193	HC SP-LENS(BEARING STRENGTH)
97	129	CHEM REACTIVITY DET(CHEM REACT)
83	202	VO (EFFECTS THERMAL CYCLING)
82	205	VO (VAC. OUTGAS.)
8	3	VO MAPS (X SECT TOPO)
1	195	HC SP-LENS (88AB)
90	125	SURVEY RATE METER(36AB)
1	176	HC LEM TARGET(SS +SIP DISTANCE)
4	87	VO MAPS INCL (SLOPE)
100	127	PARTICLE SPEC(37AB)
17	196	SAMPLING PACK.(SOIL DENSITY)
15	169	THERM PROBE(LAND GEAR THER COND)
2	1	VO HL JS (DUST TEXT,CONSIS,COMP)
1	194	HC SP-LENS (STRAT.ELEM. OF SOIL)
32	82	GYRO INCL(A3 TO SAMP SITE + SIP)
9	71	VO HL ST(ORE MINER KIND + AMT)
1	123	SAMP CULT RADIOISO RO(LIFE FORM)
6	216	VO (SOIL COLOR)
11	155	GM (GRAVITY)
15	124	SOLAR PLAS SPEC (35AB)
7	156	GRADIOMETER(GRAVITY GRADIENT)
7	137	TI HM(VER HOR VECT SUM DIR MAGF)

APPENDIX H

THEORY OF RADIATION FLUX MEASUREMENT BY MEANS OF SUSPENDED DISK RADIOMETER

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THEORY OF RADIATION FLUX MEASUREMENT BY MEANS OF SUSPENDED DISK RADIOMETER

A small disk is placed above the lunar surface at a distance that is large compared to the diameter of the disk but near enough to the lunar surface so the disk's inner side sees essentially a full hemisphere of lunar surface and its outer side sees a full hemisphere of low-temperature space. In the simplest case, the disk is in the shadow area of the moon -- not exposed to sunlight. In the general case, the disk is exposed to sunlight as well as to lunar thermal radiation.

Consider first an area of lunar surface not exposed to solar radiation. There is a flux per unit area* of radiation from the lunar surface to space. This flux can be measured by measuring the temperature of a simple disk suspended some reasonable distance (for example, 1 ft) above the surface. If the disk is entirely flat, thin, black, and mounted in a horizontal plane parallel with the surface, it receives radiation from the lunar surface on its underside, absorbs all of this radiation and reradiates this energy to space. The disk comes to an equilibrium temperature T_p. This temperature, if measured with a thermocouple or resistance thermometer, provides the necessary information to determine the radiant flux from the lunar surface.

Such a suspended disk radiometer appears to comprise a more reliable instrument for measuring heat flux than a variety of more complex radiation measuring instruments which may be influenced by the temperature of the housing or require calibration.

The disk contains a thermocouple or resistance thermometer with electrical leads running from it to the measuring circuits. These leads constitute a potential heat leak but have approximately the same radiation characteristics as the disk itself. Although the leads are at a different height above the lunar surface (through most of their path) than the disk, they reach the same temperature.

In the general case, the experiment will be carried out either in solar illumination or in shadow. Following are the radiation sources that are present.

*In the discussion, flux will be taken to mean flux per unit area from the lunar surface.

(1) The disk receives on its underside the radiation from the lunar surface.

(2) The disk receives on its underside the solar radiation reflected from the lunar surface back onto the disk.

(3) The disk receives on its outerside direct solar radiation.

(4) The disk receives on its outerside thermal radiation from space.

(5) The disk receives on its underside that radiation from space that is reflected from the lunar surface back onto the disk.

(6) The disk receives thermal radiation from the earth.

(7) The disk receives reflected solar radiation from the earth (earth shine).

Only the first three sources (1), (2), (3) are significant. The remaining sources (4), (5), (6), (7) are negligible. Radiation from the earth reaching the moon is the largest of the last four terms in its potential interference with a lunar surface flux measurement. Thermal radiation from the earth and reflected solar radiation from the earth (earth shine) at the moon are both less than 1/100th of the intensity of the lowest value of thermal radiation emitted by the lunar surface. Therefore, since all radiation from the earth (6), (7) is less than the basic experimental error in the lunar flux measurement itself, the earth radiation [as well as the other lesser terms (4), (5) due to space radiation] may be neglected.

The disk reradiates to two heat sinks.

(1) The disk radiates to space.

(2) The radiation from the disk toward the lunar surface also acts as though it were being radiated into space for the following reasons: as the radiation leaves the disk and hits the moon, a certain fraction is absorbed and the remaining fraction reflected from the lunar surface; however, the disk is so small compared to the expanse of surface viewed that the fraction of radiation from the disk that is reflected back onto it is negligible. Therefore, all radiation leaving the disk towards the lunar surface is also lost and the disk sees a fully absorbing blackbody (space) in either the moonward or spaceward direction.

Equating the significant terms of the in-going and out-going radiation to the disk at equilibrium gives

$$Q_m = \epsilon_{mt} \sigma T_m^4 \tag{1}$$

$$\left[\epsilon_{mt} \sigma T_m^4\right]\left[A\alpha_{dt}\right] + \left[S_o \operatorname{Cos} \theta\right]\left[A \alpha_{ds}\right] + \left[r_{ms} S_o \operatorname{Cos} \theta\right]\left[A\alpha_{ds}\right] = 2A\epsilon_{dt} \sigma T_d^4 \tag{2}$$

where Q_m = thermal flux leaving the lunar surface per unit area as a function of time

ϵ_{mt} = thermal total emittance of the lunar surface

ϵ_{dt} = thermal total emittance of the disk

σ = Stefan-Boltzmann constant $\left(5.669 \times 10^{-12} \frac{W}{cm^2\ {}^oK^4}\right)$

T_m = temperature of lunar surface ^oK

T_d = temperature of disk ^oK

A = area of disk cm^2 (one side)

α_{dt} = absorptance of disk to thermal radiation

α_{ds} = absorptance of disk to solar radiation

S_o = solar constant at the moon

θ = angle from the vertical at which solar radiation arrives at the disk (also equal on the average to the angle at which solar radiation arrives at the lunar surface in the region of the measurements)

r_{ms} = diffuse reflectivity of the moon's surface to solar radiation (albedo)

By Kirchhoff's relation, the absorptance and emittance of a body are equal, providing that the same spectral region and distribution of wavelengths are considered. The wavelength distribution of the lunar surface and disk is not the same because the two are at different temperatures. However, equivalence between absorptance and emittance is quite insensitive to moderate shifts of the peaks of the thermal radiation curve, so that the two may be considered entirely equivalent. An attempt to equate absorptance at the solar distribution peaked at 1/2 micron with emittance at lunar temperatures peaked between 7 and 20 microns, however, would be too extreme and could be expected to cause an unacceptable error.

Thus, we may equate

$$\alpha_{dt} = \epsilon_{dt} \tag{3}$$

and rewrite Eq. (2) as

$$Q_m = 2\sigma T_d^{\ 4} - \frac{\alpha_{ds}}{\epsilon_{dt}} \left[1 + r_{ms}\right] S_o \operatorname{Cos} \theta \tag{4}$$

Thus, the lunar flux per unit area is expressed in terms of the disk temperature, the disk "alpha over epsilon", the lunar albedo, the solar constant outside the earth's atmosphere and the angle from the vertical at which the sun's rays arrive at the lunar surface.

It is possible to prepare metal or other surfaces that are quite black to a wide range of wavelengths (e.g. Parson's black is 98 per cent black or better through the visible to 14 microns). If the disk can be made black, $\alpha_{ds} = \epsilon_{dt} = 1$ and Eq. (4) becomes

$$Q_m = 2\sigma T_d^{\ 4} - \left[1 + r_{ms}\right] S_o \operatorname{Cos} \theta \tag{5}$$

Putting in the following values: lunar albedo $r_m = 0.073$, S_o outside the earth's atmosphere = $0.139 \dfrac{\text{watts}}{\text{cm}^2}$

$$Q_m = 2\sigma T_d^{\ 4} - 0.149 \operatorname{Cos} \theta \tag{6}$$

The errors to be expected in a flux measurement on the lunar surface can be estimated at least as to the range in which they are likely to fall. The errors are different depending on whether the measurement is carried out during lunar day or lunar night.

During lunar night, Eq. (6) reduces to

$$Q_m = 2\sigma T_d^{\ 4} \tag{7}$$

and the percentage error

$$\frac{\Delta Q_m}{Q_m} = \frac{4 \Delta T_d}{T_d} \tag{8}$$

depends only on the accuracy with which the temperature of the disk can be measured. If we make the (conservative) assumption that the temperature can be determined to within ± 1 per cent of its absolute value, the lunar thermal surface flux during night can be known to be ± 4 per cent.

The one other potential source of error in this measurement, the blackness of the disk, does not give rise to comparable errors. The disk can be made at least 98 per cent black to all radiation and its emittance measured. Thus, the extent to which the disk emittance is unknown leads to negligible error, at least on the earth's surface. This error could become larger in the lunar environment due to such factors as proton bombardment or dust deposition on the disk.

When the flux measurement is carried out during lunar day, two sources supplying radiant heat to the disk, Q_m and $(1 + r_m) S_o \cos \theta$, are about equal in magnitude. Regarding the solar term, the value of albedo, r_{ms}, is so low as to make the effects of uncertainty in albedo unimportant. Therefore, the major uncertainty is in the solar constant itself, S_o. The solar constant is known to vary by ± 2 per cent. Therefore, the total percentage error in the determination of Q_m may be taken to be in the range of the square root of the sum of the squares of: the temperature determination error above and the error in the solar constant; about ± 5 per cent overall.

If required, the accuracy of lunar surface flux determination could be improved to ± 3 per cent by refinement of temperature measurement techniques and by use of an instrument in the space vehicle to monitor independently the solar constant.

For instrumenting the suspended disk, there is an alternative means that may lead to improved accuracy and reliability. In this alternative method, the disk is made as a heat flow meter of the type described earlier. Differential thermocouples are used, one junction on each side of the disk (in practice, thermopiles are used). Heat flow through the disk causes a slight temperature difference between the faces which is measured by the thermocouples. Thus, a temperature difference rather than a temperature is measured at the disk.

The basic advantage of this system is that both junctions (hot and cold) are in the disk, the two conductors carrying the electrical signal from the disk are of the same (rather than dissimilar) metals, no cold junctions (spurious or deliberate) are set up elsewhere in the system, and the problem of reference and calibration is greatly simplified.

Consider the heat arriving at and leaving each face of the disk. The temperature differential across the disk is considered slight enough so that the disk may be considered at one temperature T_d as far as radiation from it is concerned. For the moonward face,

$$Q_m + r_{ms} S_o \operatorname{Cos} \theta + F - \sigma T_d^4 = 0 \tag{9}$$

and for the spaceward face,

$$S_o \operatorname{Cos} \theta = \sigma T_d^4 - F = 0 \tag{10}$$

where F = the flux through the disk per square centimeter. Combining Eq. (9) and (10) and rearranging,

$$Q_m = -2F + \left[1 - r_{ms}\right] S_o \operatorname{Cos} \theta \tag{11}$$

The errors in this method of lunar surface flux measurements are comparable with those of the disk temperature method. Assuming that the disk determines the flux to ±2 per cent, then from Eq. (11) it can be shown that the error in lunar flux (per unit area) will be twice the measurement error. Therefore, the likely measurement error is ±4 per cent, similar to the error in the disk temperature method.

If the lunar flux per unit area is determined by either method and a reasonable value of lunar surface emittance is estimated, a reasonably accurate estimate of lunar surface temperature can be made from the Stefan-Boltzman equation for nonblack bodies.